Human Temperature Regulation in Wind and Waves

By

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The thesis is submitted in partial fulfillment of the requirements for the award of the degree of Doctor of Philosophy of University of Portsmouth

Portsmouth

July 2012

Abstract

Many international and national standards exist for the testing and certification of immersion suits. Some require the thermal protective properties of immersion suits to be tested with human volunteers in calm, circulating 2°C water. The knowledge gap that currently exists between the benign testing conditions used in international standards and specifications, and the harsh environments that an immersed individual find themselves in following a marine accident, could result in unexpectedly poor levels of performance, with fatalities occurring sooner than expected following accidental immersion.

Study 1 determined the heat loss from the skin of volunteers in immersion suits and immersed in wind and waves. Twelve healthy participants (Age: 25.8 [5.9] years old; Mass: 81.7 [13.1]kg; Height: 176.2 [7.7]cm) performed four, one hour immersions in the following conditions: Calm water; Wind-only; Waves-only; and Wind + Waves. Compared to Calm (67.21 [4.70]$W \cdot m^{-2}$), all the other immersion conditions produced a significantly greater increase in mean skin heat flow (MSHF) (Wind: 79.60 [6.70]$W \cdot m^{-2}$; Waves: 78.8 [4.52]$W \cdot m^{-2}$; Wind + Waves: 92.00 [8.39]$W \cdot m^{-2}$). The Wind + Waves condition produced a significantly greater increase in MSHF compared to all other conditions.

Study 2 built upon the findings of the first by investigating the extent to which human thermal responses were related to the severity of weather conditions. Twelve healthy males (Age: 23.9 [3.3] years old; Mass: 83.2 [4.9]kg; Height: 181.0 [4.9]cm) performed three, three hour immersions in the following conditions: Calm water; Weather 1; and Weather 2. Compared to the calm water condition (62.96 [2.98]$W \cdot m^{-2}$], both weather conditions produced a significantly greater increase in MSHF (Weather 1: 76.75 [6.26]$W \cdot m^{-2}$; Weather 2: 79.53 [6.24]$W \cdot m^{-2}$). There were no significant differences in the change in gastro-intestinal temperature (T_{GI}) across immersion conditions (Calm: -0.10 [0.31]°C; Weather 1: -0.29 [0.30]°C; Weather 2: -0.20 [0.28]°C]. There were no significant differences in $\dot{V}O_2$ across immersion conditions (Calm: 0.325 [0.054]$L \cdot min^{-1}$; Weather 1: 0.332 [0.108]$L \cdot min^{-1}$; Weather 2: 0.365 [0.080]$L \cdot min^{-1}$).

Study 3 investigated the effect of simulated water ingress under an immersion suit on human thermal responses during immersions in varying weather conditions. Twelve healthy males (Age: 25.6 [5.6] years old; Mass: 82.7 [10.2]kg; Height: 181.0 [4.7]cm) performed three, three hour immersions in the same conditions as Study 2, but with 500mL of water underneath the immersion suit. Compared to the calm water condition (79.45 [9.19]$W \cdot m^{-2}$), both weather conditions produced a significantly greater increase in MSHF (Weather 1: 102.06 [11.98]$W \cdot m^{-2}$; Weather 2: 107.48 [3.63]$W \cdot m^{-2}$). There were no significant differences in the change in T_{GI} (Calm: -0.35 [0.14]°C; Weather 1: -0.38 [0.15]°C; Weather 2: 0.29 [0.25]°C) or $\dot{V}O_2$ (Calm: 0.449 [0.054]$L \cdot min^{-1}$; Weather 1: 0.503 [0.051]$L \cdot min^{-1}$; Weather 2: 0.526 [0.120]$L \cdot min^{-1}$) across conditions.

Survival times were calculated for the participants of Studies 2 and 3. There was no difference in the predicted survival times for the Study 2 participants for both the calm (> 36 hours) and wind and wave conditions (> 36 hours). The predicted survival times for the participants of Study 3 were significantly lower in the turbulent conditions (16 hours) compared to calm (27 hours). The predicted survival times of the participants in turbulent conditions were up to half those calculated for calm water immersions.

The results collected in Studies 2 and 3 were used to calculate the change in total insulation in varying conditions compared to being dry. Immersions in wind and waves will reduce immersion suit insulation by 27%; 500mL of water leakage will reduce it by 24%; wind, waves and 500mL of water combined will reduce it by 43%.

The predicted amount of oxygen consumption ($\dot{V}O_{2\ P}$) to produce the amount of heat required to remain in thermal balance can be estimated by rearranging the equations used to calculate metabolic heat production and insulation. If heat loss exceeds the assumed maximum heat production of 206$W \cdot m^{-2}$, hypothermia will eventually develop. The point at which heat loss exceeds maximum heat production has been determined in a range of conditions.

It is concluded that: immersions in wind and waves causes a significant increase in heat flow from the body compared to calm conditions. Testing individuals and immersion suits in conditions not representative of the area where they are to be used may, or may not, result in an over-estimation of performance depending on the capacity of an individual's thermoregulatory system.

Declaration

"Whilst registered as a candidate for this degree, I have not been registered for any other research award. The results and conclusions embodied in this thesis are the work of the named candidate and have not been submitted for any other academic award"

Jonathan Power

Acknowledgements

Many different people and organizations contributed to the work described in this thesis who I would like to thank.

Professor Michael Tipton for agreeing to take me on as his student, and for having endless reserves of patience with me over the years as I created new scientific terms, telephoned fax lines, and accidentally got things right. Professor Tipton has been an incredible mentor to me throughout this process and I am very thankful to have had the opportunity to study under him.

Dr. Martin Barwood for all his incredibly helpful support and encouragement throughout the entire Ph.D. program. The process of writing this thesis was made much easier with the support and positive comments from Dr. Barwood.

My colleague and friend, Lise Petrie, for being with me every step of the way on all the projects. Through all the long test days and setbacks, the two of us always managed to get the work done.

Dr. Scott MacKinnon for being a trusted friend and colleague throughout the years, and always supporting me in all my endeavours.

Dr. Chris Brooks for his generosity in helping me start these projects after I called him out of the blue one day.

Dr. Peter Tikuisis for agreeing to help me with survival time modelling, and always being a pleasure to work with.

All my colleagues at the National Research Council of Canada's Institute for Ocean Technology for working with me on these projects. The studies would not have been completed without their skills, knowledge, and creativity.

I am grateful to Transport Canada and the Program of Energy Research and Development for their financial support of this work.

A very big thank you to all my participants who volunteered for the studies. This work would have never been completed without them, and they were all pleasures to work with.

There is one person I want to thank most of all. It is no exaggeration to say that this work would never have been completed (or even started) if not for my good friend, trusted colleague, and mentor, António Simões Ré. From the first day I started with NRC, I have been able to approach António about any topic, and always receive his passionate support. António has pushed me to achieve things that I had believed were beyond my capability to do so. António is a recognized world leader in Marine Safety and I have been incredibly fortunate to work alongside him on many projects. Thank you, António, for always supporting and encouraging me in all my work.

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List of Abbreviations

Abbreviation	Definition
ANS	Autonomic nervous system
CESM	Cold Exposure Survival Model
CGSB	Canadian General Standards Board
CSR	Cold shock response
FRC	Fast rescue craft
IMO	International Maritime Organization
ISO	International Organization for Standardization
LSA	Life saving appliance
$\dot{M}$	Metabolic heat production ($W \cdot m^{-2}$)
MSHF	Mean skin heat flow weighted according to regional surface area ($W \cdot m^{-2}$)
$MSHF_P$	Predicted mean skin heat flow ($W \cdot m^{-2}$)
NRC-IOT	National Research Council of Canada – Institute for Ocean Technology
OEB	Offshore Engineering Basin
REB	Research ethics board
SA	Surface area of the body (m^2)
SAR	Search and rescue
TIM	Thermal Instrumented Manikin
T_{DB}	Deep body temperature (°C)
T_{GI}	Gastro-intestinal temperature (°C)
ΔT_{GI}	Change in gastro-intestinal temperature (°C)
T_{RE}	Rectal temperature (°C)
$\overline{T}_{SK}$	Mean skin temperature weighted according to regional surface area (°C)
$\Delta\overline{T}_{SK}$	Change in mean skin temperature (°C)

$\dot{V}e$	Volume of gas exhaled from the body per minute ($L \cdot min^{-1}$)
$\dot{V}CO_2$	Volume of carbon dioxide produced per minute ($L \cdot min^{-1}$)
$\dot{V}O_2$	Volume of oxygen consumed per minute ($L \cdot min^{-1}$)
$\dot{V}O_{2\ kg}$	Volume of oxygen consumed per kilogram of body weight per minute ($mL \cdot kg^{-1} \cdot min^{-1}$)
$\dot{V}O_{2\ P}$	Predicted volume of oxygen consumed per minute ($L \cdot min^{-1}$)

Chapter 1 – Introduction

1.1 Statement of the problem.

Across the world, many individual in different industries work or travel over open water. Since the majority of the planet is covered in water that is below thermoneutral temperatures (33-35°C), the use of life saving appliances that offer thermal protection is often required to improve the safety of individuals at sea. Lifeboats and liferafts are two common Life Saving Appliances (LSA) required to be carried by vessels operating in the open ocean, and even the helicopters that fly daily to the offshore oil installations are equipped with liferafts. Both lifeboats and liferafts are designed to help improve the survivability of their occupants by providing a temporary refuge from the environment; keeping them out of the frigid waters which can pose the greatest threat to survival.

Immersion in cold water can be a serious threat to a person's survival in both the short and long term. Fatalities due to cold water immersion are often incorrectly attributed to significant cooling of the deep body temperature; however most fatalities due to cold water immersion occur in less than 15 minutes, whereas it can take even a lightly clothed individual at least 30 minutes to develop hypothermia in 0°C water (Hayward and Eckerson, 1984). The Royal College of Physicians London (RCPL) define hypothermia as a drop in deep body temperature below 35°C (RCPL, 1966). The initial responses to cold water immersion also pose a significant threat before the onset of hypothermia. Sudden immersion in cold water results is a series of physiological responses termed the Cold Shock Response (CSR) (Tipton, 1989). The CSR includes: an increase in heart rate (*tachycardia*); a large involuntary gasp; increased breathing rate (*hyperventilation*), and constriction of the peripheral blood vessels (Keatinge and Evans, 1961).

An immersion suit is a LSA designed to protect an immersed individual from the CSR, delay the onset of hypothermia, and provide flotation (CGSB, 2005). In Canada, immersions suits are required by regulatory bodies to be carried on fishing vessels in sufficient quantities for each crew member to have one, and they are to be worn at all times by persons commuting via helicopter to offshore oil installations.

In Canada, immersion suits are required to undergo a variety of tests outlined by the Canadian General Standards Board (CGSB) before being certified for use in the offshore industries. These tests include flotation stability, the ability to move to a vertical position while immersed, durability, water ingress (leakage), and thermal insulation. Current CGSB testing standards of the thermal insulation of immersion suits are conducted on a thermal manikin or human participants. In human participant tests, a volunteer must don a suit and be immersed in calm, circulating 2°C water for six hours (CGSB, 1999; CGSB, 2005). If the suit prevents the participant from developing hypothermia in the six hour test, then it passes.

Even though immersion suits are used throughout the world, and tested according to various national and international standards, immersion-related deaths still occur. In recent years, multiple marine accidents have called into question the level of thermal protection provided by immersion suits, and the standards they are designed to meet.

In February of 2008 the *Check Mate III* capsized off the north east coast of Newfoundland, eastern Canada. Both crewmembers were able to successfully radio for help, don their immersion suits, and abandon ship into the Atlantic Ocean which had a temperature of 0.8°C at the time (MRSC 2008). A Search and Rescue (SAR) helicopter was able to locate the two-crew members within approximately an hour and half of having entered the water. Knowing that a SAR Fast Rescue Craft (FRC) was only 20 minutes away from the crewmembers, the decision was made to wait for the FRC to retrieve them. By the time the FRC was able to retrieve the men from the water they had both perished. The subsequent investigation into the tragedy revealed that the men's immersion suits had failed "in a spectacular fashion." (MRSC, 2008). If the suits had indeed met the thermal protective properties as described in CAN/CGSB 65.16-2005, they should have prevented the victims from developing hypothermia in less than six hours.

On March 12th, 2009 Cougar Flight 491 crashed into the Atlantic Ocean (with a water temperature between0.1-0.3°C at the time of the crash [TSB, 2010]) approximately 50 kilometers east of St. John's, Newfoundland. The sole survivor of the crash, Mr. Robert Decker, was able to successfully escape from the sinking helicopter and made it to the surface. Mr. Decker was in the water for approximately 90 minutes before SAR technicians deployed by helicopter rescued him. Upon arriving at the hospital, two hours after the initial crash, Mr.

Decker's immersion suit was completely filled with water, and his deep body temperature was 28°C (TSB, 2010).The immersion suit he was wearing was designed to prevent a drop in deep body temperature of 2°C for at least six hours in 2°C water.

The tragedies of both the *Check Mate III* and Cougar Flight 491, along with others, raise questions about the performance of immersion suits, and if they are capable of providing the level of protection required of them.

A knowledge gap currently exists between the testing standards outlined in the CGSB and other standards for the thermal protective properties of immersion suits, and their performance in the rougher conditions that can occur during marine accidents. The current CGSB, International Organization for Standardization, and International Maritime Organization standards require that immersion suits need only be tested in "calm, circulating water", yet rougher conditions occur in the North Atlantic Ocean where individuals work and travel every day. Climatic data for the east coast of Canada (Grand Banks) in early 2010 are given in Table I. Clearly, the conditions experienced are rarely "calm, circulating water". The discrepancy between the benign testing conditions, and those found in the open ocean can result in what Tipton has referred to as "surprisingly poor performance in a real accident" (Tipton, 1995), leading to fatalities at sea.

Table 1.1. Climatic data for south-western portion of the Grand Banks, Canada.[1]

Month (2010)	Significant Wave Height[2] (m) [SD]	Wind Speed ($m \cdot s^{-1}$) [SD]	Air Temperature (°C) [SD]	Water Temperature (°C) [SD]
Jan	3.48 [1.10]	9.59 [4.13]	2.5 [3.1]	4.3 [1.5]
Feb	4.06 [1.45]	10.37 [4.90]	0.7 [2.3]	2.7 [1.0]
Mar	2.64 [1.14]	4.06 [4.88]	2.0 [1.8]	2.2 [0.9]
Apr	2.10 [0.78]	4.23 [3.87]	4.3 [1.3]	4.1 [0.6]

The purpose of the work described in this thesis was to examine the change in the thermoregulatory responses of humans in immersion suits when moving from the calm water

[1] From Fisheries and Oceans Canada (www.dfo-mpo.gc.ca).
[2] Significant wave height is defined as the mean wave height of the highest third of the waves.

conditions often used for certification, to more turbulent environments commonly found at sea. Knowledge of the effect of this change in conditions should provide a better evidence-base for the design of realistic immersion suit testing and SAR policies, and thereby an improvement in the safety of persons at risk of accidental immersion in cold water.

1.2 Summary of Individual Chapters.

The present chapter provides background information on the knowledge gap that the research in this thesis addresses. The second chapter discusses literature relating to the physiological responses to immersion in cold water, describing the four stages associated with particular hazards on immersion. The chapter continues by reviewing past work that has investigated the change in thermoregulatory responses when moving from calm water conditions to those with wind and waves. Finally, the use of thermal manikins as tools for certifying immersions suits is reviewed in conjunction with how the test results correlate with human thermal responses.

Chapter Three includes the details of the equipment and procedures that were common throughout all the studies in this thesis. The chapter continues by discussing study-specific equipment and methods.

The first study (Study 1) investigated the effect of wind and waves on skin heat flow and is presented in Chapter Four. This study had two aims: firstly, to develop the resources and capabilities of the National Research Council of Canada's Institute for Ocean Technology (NRC-IOT) for human testing. Secondly, to quantify the effect that wind and waves, both individually and in combination, have on heat flow when compared to calm water with humans and a thermal manikin. Data from Study 1 were presented at the peer reviewed 18th International Society of Offshore Polar Engineers (ISOPE) conference, Vancouver, Canada, July 7th to 11th, 2008.

The study described in Chapter Five (Study 2) built upon the findings of the first study by investigating if human thermal responses changed in relation to varying wind and wave conditions during three-hour immersions. Data from Study 2 were presented at the peer reviewed 13th International Conference of Environmental Ergonomics (ICEE), Boston, United States of America, August 2nd to 7th, 2009.

Continuing to build upon previous work, the study presented in Chapter Six (Study 3) investigated the effect of simulated water leakage on human thermal responses in varying weather conditions. To simulate water leakage, 500mL of water was added underneath the immersion suit before participants performed three-hour immersions in the same conditions as used in Study 2.

Results from Studies 1 and 2, and the preliminary results from Study 3, were published in the report “Human Performance in Immersion Suits” submitted to the Offshore Helicopter Safety Inquiry; the commission was established to investigate the crash of Cougar Flight 491 on March 12^{th}, 2009.

The data collected from Studies 2 and 3 were compared to predicted survival times generated by Cold Exposure Survival Model (CESM) using the anthropometrics of the participants in the conditions tested; the results are presented in Chapter Seven. Additionally, the results collected from Studies 2 and 3 of the effects of wind, waves, and water leakage under the immersion suit are used to calculate the increased effort (“physiological cost”) of thermoregulation for individuals in more severe conditions (i.e. wind and waves) compared to calm water. Correction factors for testing immersion suits in calm water are presented in Chapter Eight. The assumptions and limitations of the studies of this thesis are presented in Chapter Nine, and suggestions for further research are made in Chapter Ten.

Chapter 2 – Review of Literature

A review of literature was conducted that searched for studies that examined human thermal responses in immersion suits, thermoregulatory responses to cold water immersions, thermal manikin studies and survival time prediction models. The reviews were completed using online search engines such as PubMed, using search terms such as: “Immersion in wind and waves; hypothermia; immersion suits; and thermal manikins”. Only a limited number of studies were found that related to the research question: the influence of wind and waves on thermal responses during immersion (Table 2.1, pg. 34).

An accurate assessment of immersion suit performance in offshore conditions would be extremely beneficial to marine safety due to the amount of activity that takes place on or over open water in a variety of industries. At the 2011 Newfoundland and Labrador Oil and Gas Industries Association (NOIA) meeting it was stated that off the eastern coast of Newfoundland, Canada, there are five basins that have been active for almost 40 years in producing petrol products. Remarkably, even after 40 years, these basins have not yet reached critical mass with regards to production, and it estimated that more significant petrol deposits remain to be discovered. While these basins represent only about 0.5% of the world’s total oil production, they are of vital importance to both the provincial and federal economy. As of September 2011, there were four active fields producing approximately nine million barrels of oil a month (CNLOPB, 2012). The Hebron oil field, which will start production in 2017, is estimated to contain over 700 million barrels of oil, and will generate over $20 billion dollars over the course of its 25 year life expectancy.

Given the huge financial importance to both the provincial and federal economy, the offshore oil industry in Newfoundland and Labrador will continue to be active for many years to come. Consequently, helicopters fly workers multiple times a day to the offshore oil installations, which normally have approximately 80-200 personnel on board at any given time. In addition to the personnel who work directly on the offshore platforms, there are also the support vessels that ferry supplies such as food and amenities to these installations. In conjunction with the oil industry, the offshore food fishery industry in Newfoundland is also a high revenue-generating sector, generating over $627 million dollars in 2004 (DFO, 2004), resulting in a large number of fishing vessels operating off the east coast.

The consequence of this commercial activity is a daily risk of accidental immersion in the cold waters that individuals work or travel over. Throughout the year, the environmental conditions found offshore are extremely inhospitable for humans, with the highest significant wave height measured in February 2010 being 11.06m, with wind speeds reaching up to $112 km \cdot hr^{-1}$. The temperature of the water off the east coast of Canada is well below thermoneutral values (i.e. 35°C), with the lowest water temperature measured in 2010 being approximately 2°C, and air temperature regularly dropping below 0°C.

These cold water and air temperatures represent a threat to humans, who like all homeothermic animals, require much warmer conditions to survive. Humans have been able to explore and operate in colder conditions through the use of insulating clothing and shelters, ensuring that the conditions around the body remain at thermoneutral values. Regardless of their location in the world, the mean skin temperature of a person in thermal balance without shivering or sweating will be approximately 33°C, due to the microclimate created around the skin through the use of clothing and shelter. In the absence of protection in environments that have temperatures below thermoneutral values (e.g. immersion in cold water), survival can be threatened due to increased heat loss culminating in hypothermia (Golden and Tipton, 2002).

To remain in thermal balance, the heat gained by a human must equal the heat lost. If the heat gained exceeds the heat lost, the human is in positive thermal balance and will experience a rise in stored heat, and subsequently, deep body temperature (*hyperthermia*). If the heat lost exceeds heat gain, the human will be in negative heat balance and will experience a fall in stored heat and deep body temperature (*hypothermia*). The heat balance equation is a fundamental equation of thermal physiology. It incorporates and emphasizes the routes of heat exchange between the body and the environment, and the importance of heat exchange being balanced by the body’s physiological process for retaining (vasoconstriction), generating (shivering) and losing (sweating, vasodilatation) heat. The heat balance equation is:

$$\dot{M} - W \pm R \pm C \pm K - E = 0$$

Where:

$\dot{M}$ = Metabolic rate

W = Measurable external work

R = Radiation

C = Convection

K = Conduction

E = Evaporation

All in $W{\cdot}m^{-2}$.

Heat can be exchanged through four different physical routes: conduction (K), convection (C), radiation (R), and evaporation (E) (Clark and Edholm, 1985). Conduction is the direct exchange of heat from two objects that are physically touching. Convection is the process in which a fluid is warmed causing it's density to lessen, and subsequently rise to be replaced by cooler particles. The forceful movement of the fluid (wind for air; current for water) is called "forced" convection. Radiation is the process by which all objects possessing heat emit electromagnetic waves that travel at the speed of light until they make contact with another object, transferring heat to it. Evaporation is the process in which the energy, in the form of heat, is used to transform a liquid into a gas (latent heat of vaporization). The heat is transferred from the surface that the water is resting on, causing the surface to cool. For a human immersed in cold water the two primary methods of heat exchange are conduction and convection (Golden and Tipton, 2002). The rate of convective heat loss is dependent on the velocity of the water at the surface of the body with maximum heat loss being reached around $0.75 m{\cdot}s^{-1}$ (Figure 2.1). Further increases in water velocity will result in little change in the amount of heat loss due to convection (Witherspoon et al., 1971).

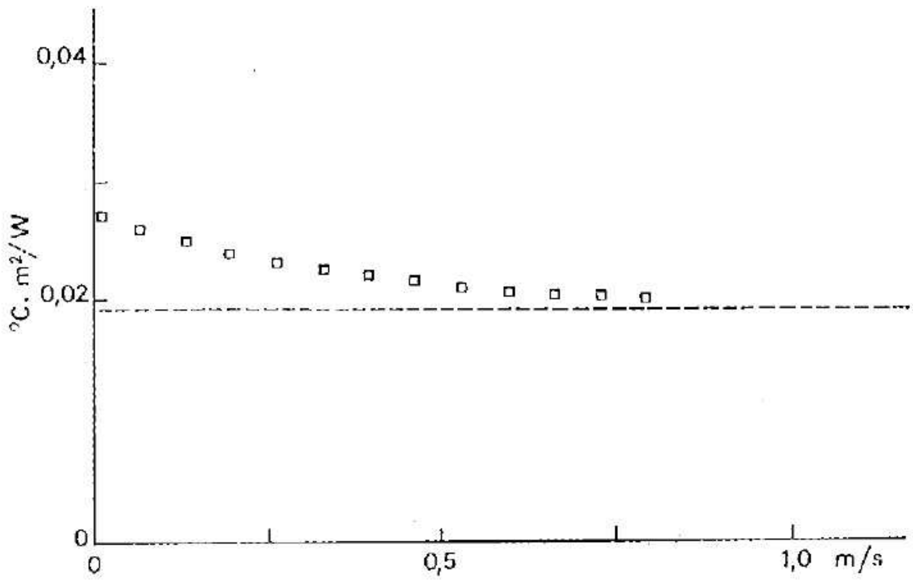

Figure 2.1. Thermal resistance of a nude copper manikin upright in 20°C cross flowing water (Horizontal axis: water velocity [$m \cdot s^{-1}$], vertical axis: thermal resistance [$°C \cdot m^2 \cdot W^{-1}$], from Witherspoon et al. [1971]).

Changes in body temperature due to environmental heat exchange are detected by thermoreceptors located in the superficial sub-epidermal layers of the skin (peripheral receptors) and within the body itself, especially the hypothalamic structures of the brain (central receptors) (Clark and Edholm, 1985). The inputs from these thermoreceptors are integrated into the hypothalamus which also controls thermoregulatory responses (Clark and Edholm, 1985). Thermoreceptors are categorized into two groups: “cold receptors” that increase their firing frequency when cooled; and “warm receptors” that increase their firing frequency when warmed (Figure 2.2) (Hensel, 1981). There is a small temperature range where the firing frequencies of both cold and warm receptors are equal; this temperature range is associated with a skin temperature between 33-35°C (Hensel, 1981) (Figure 2.2).

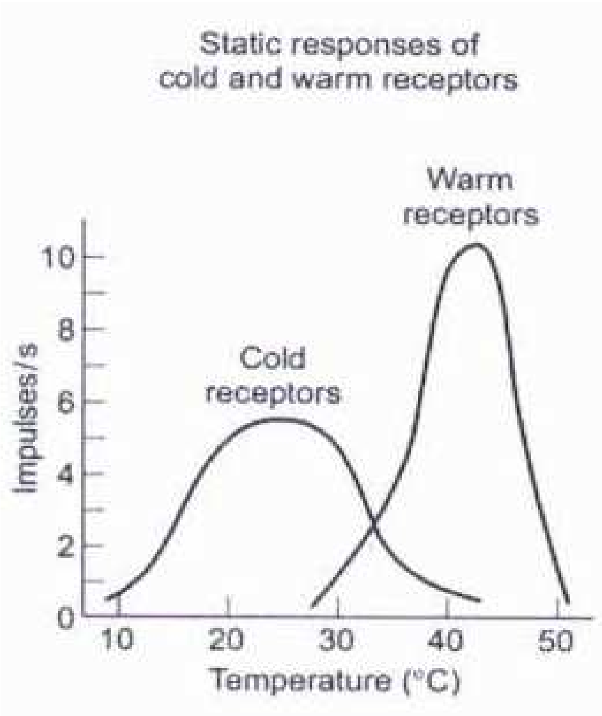

Figure 2.2. Firing frequency of cold and warm thermoreceptors at varying temperatures (From Tipton [2006]).

It is suggested that thermoregulation is achieved via cross-inhibition between the thermoreceptors, as opposed to the body attempting to maintain a specific temperature that matches a reference value (analogous to a thermostat in a house controlling temperature) (Mekjavic and Eiken, 2006). As cold thermoreceptors begin firing they stimulate the appropriate responses to cooling (vasoconstriction and shivering) while inhibiting the responses to warming (vasodilatation and sweating). Warm receptors follow the same cross-inhibition mechanism: they stimulate thermoregulatory responses to warming while inhibiting those associated with cooling (Figure 2.3).

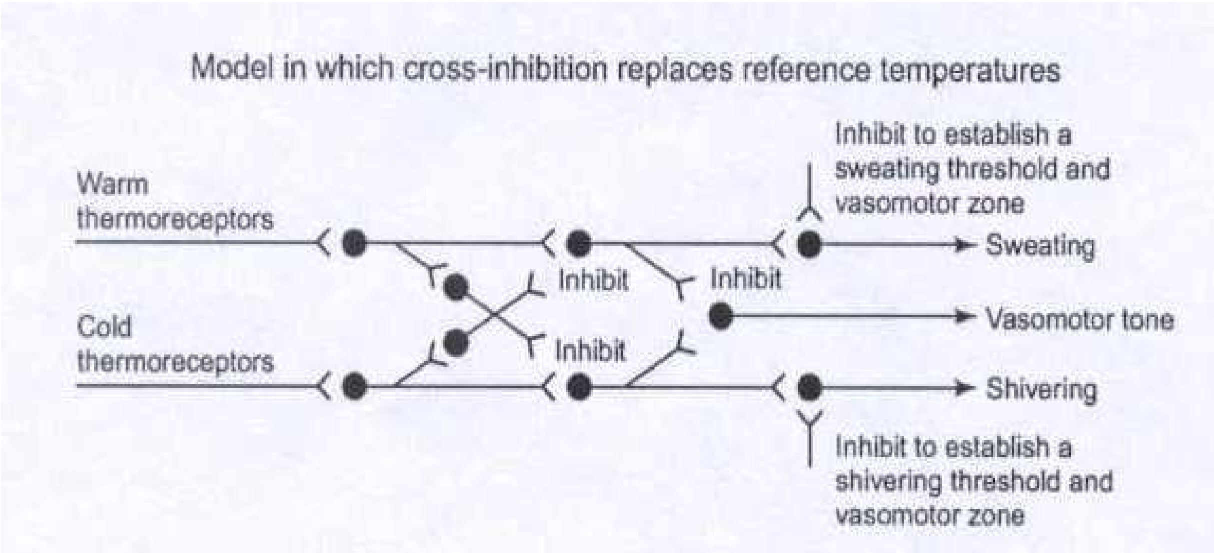

Figure 2.3. Cross-inhibition thermoregulatory model (From Mekjavic [2003] in Tipton [2006]).

Stimuli from central thermoreceptors will have a greater effect on the magnitude of thermoregulatory responses initiated by the hypothalamus compared to the peripheral (Tipton, 2006). The zone in which body temperature can be regulated by simply changing blood flow (and therefore heat delivered to the skin) has been called the "vasomotor zone"; "inter-threshold zone", " dead band" or "thermoneutral zone" (Mekjavic et al., 2003). This zone has been observed to range between a $\overline{T}_{SK}$ of 33-35°C (Savage and Brengelmann, 1996). It is in this zone that heat balance is achieved by controlling the amount of blood flow to the surface of the skin through either vasoconstriction or vasodilatation (Mekjavic and Eiken, 2006). Through the activation of the sympathetic branch of the autonomic nervous system (ANS), and release of norepinephrine, smooth muscles controlling blood flow contract to reduce flow through peripheral vessels and achieve vasoconstriction. Vasodilatation is thought to be due to removal of vasoconstrictor tone, with some regions having active vasodilatation (Kellogg et al., 1995).

Outside the thermoneutral zone shivering and sweating are utilized to help maintain a stable temperature; physiological processes that consume stored energy (for shivering) and water (for sweating). In response to falling body temperature, shivering is initiated via the posterior hypothalamus and results in the involuntary simultaneous asynchronous and rhythmic contractions of skeletal muscle motor units to increase heat production (Clark and Edholm, 1985).

If body temperature rises past the point where vasodilatation is insufficient to help regulate it, sweating is initiated (Tipton, 2006). Sweat evaporation through the heat lost by the latent heat of vaporisation, not sweat production, is responsible for cooling the body, which is why the cooling power of sweat is significantly reduced in humid environments (Golden and Tipton, 2002). The zone in which the body can thermoregulate, by shivering or sweating, has been termed the "thermoregulatory zone"; beyond this zone, body temperature will rise towards hyperthermia, or fall towards hypothermia, despite sweating or shivering. As humans cool, vasoconstriction and shivering are the two most important physiological responses to help remain in thermal balance and defend against a reduction in deep body temperature.

On cold exposure, vasoconstriction helps achieve thermal balance by reducing the volume of blood delivered to the surface of the skin, thereby helping to decrease the amount of heat lost to the external environment. Secondly, it withdraws the blood below the subcutaneous fat which has an insulation value similar to cork (Golden and Tipton, 2002).

The insulation provided by the body can be considered "internal" insulation, while that provided by clothing can be considered "external". Internal insulation is composed of the skin, subcutaneous fat and unperfused muscle. Unperfused muscle can provide up to 85-90% of total internal insulation (Veicsteinas et al., 1982). This insulation is called "variable" since the amount of insulation it provides can change depending on the amount of blood perfusing it; blood flowing though the muscle, as a result of exercise (including shivering) for example, will reduce the amount of insulation it provides. Subcutaneous fat is considered "fixed" since the amount of insulation it provides is constant regardless of the changes in peripheral and cutaneous blood flow due to vasoconstriction. The amount of subcutaneous fat is specific to the individual. The maximum level of vasoconstriction observed, and therefore greatest level of insulation achieved due to unperfused skin, occurs when mean skin temperature is below 30°C (Barcroft and Edholm, 1943). If skin temperature remains above 30°C, cutaneous vasoconstriction may not be at a maximum level (Barcroft and Edholm, 1943).

2.1 Sudden Cold Water Immersion.

Immersion in cold water represents a significant risk to individuals who work or travel over it. If an unprotected human is suddenly immersed in cold water, a series of physiological responses termed the "Cold Shock Response" (CSR) occurs and may be responsible for the majority of drowning deaths within the first few minutes of immersion (Tipton, 1989). The physiological responses upon initial immersion in cold water include: a large involuntary gasp, hyperventilation, tachycardia, hypertension and peripheral vasoconstriction (Tipton, 1989). The CSR is triggered by a rapid fall in skin temperature, specifically by the firing of cutaneous thermoreceptors that are stimulated by cold (Goode et al., 1975; Cooper et al., 1976; Mekjavic et al., 1987). These thermoreceptors are superficially located in the sub-epidermal layers, consequently subcutaneous fat does not attenuate the magnitude of the CSR (Cooper et al., 1976). When activated, the thermoreceptors stimulate the sympathetic branch of the ANS (Johnson et al., 1977; Galbo et al., 1979).

For a healthy individual, it is the respiratory component of the CSR that represents the greatest threat to survival after sudden immersion. The large involuntary gasp (Keatinge and Nadel, 1965) and hyperventilation (Keatinge and Nadel, 1965; Cooper et al., 1976) that ensues is known to make breath holding extremely difficult (Tipton and Vincent, 1989). The gasp response can reach values as much as 3L over a duration of 1.2 seconds in cold water (Goode et al., 1975), and the hyperventilation can reach five times resting values (Hayward and Eckerson, 1984). In the initial few minutes of immersion in cold water, the inability to breath-hold will greatly increase the chance of aspirating water and drowning (Tipton and Vincent, 1989). As well, the hyperventilation makes swimming difficult, as it becomes near impossible to coordinate breath holding with swimming (Golden et al., 1986). Previous work has shown aspirating as little as $22 mL \cdot kg^{-1}$ of body mass (or 1.58L of water for a 75 kg person) is sufficient to result in drowning (Modell et al., 1966). It is the inability to breath hold that can cause individuals to perish quickly in cold water, often whilst extremely close (< 10m) to shore (Home Office, 1977). The largest respiratory responses seen in the CSR occur when the upper torso is cooled, compared to the lower torso and limbs (Burke and Mekjavic, 1991). It is believed that the upper torso may have a greater influence on the ANS compared to the extremities (Burke and Mekjavic, 1991). Additionally, prolonged hyperventilation results in a significant reduction in carbon dioxide levels in the blood (*hypocapnia*) (Cooper et al., 1976). This hypocapnia can cause cerebral hypoxia due to a reduction in cerebral blood flow and a left shift in the oxy-haemoglobin dissociation curve (Tipton, 1989). The resulting cerebral hypoxia is thought to be the cause of the disorientation experienced by individuals upon sudden immersion in cold water (Cooper et al., 1976). Hypocapnia can also result in decreased grip strength due to decreased nerve conduction velocity and delayed response to direct muscle stimulation, which would reduce the effectiveness of the arms when performing a self-rescue action such as climbing a rope ladder onto the deck of a vessel (Cooper et al., 1976).

In addition to the respiratory responses, the CSR also includes cardiovascular components. The two primary cardiovascular responses seen are tachycardia and vasoconstriction. The tachycardia produced by the CSR can result in a heart rate increase of approximately 49% compared to pre-immersion values (Hayward and Eckerson, 1984). The vasoconstriction caused by immersion in cold water can reduce peripheral blood flow up to 80% compared to immersions in thermoneutral water (Barcroft and Edholm, 1943); the consequent increase in total peripheral resistance culminates in increased cardiac strain and hypertension (Tipton, 1989). Individuals who suffer from pre-existing cardiovascular conditions may be at increased risk, as the stress placed on the heart by the increased heart rate and narrowing of blood vessels may result in myocardial ischaemia (Tipton, 1989). For healthy individuals, the cardiovascular components of the CSR pose little threat to survival, however the co-activation of the autonomic nervous system by breath holding, or face immersion during cold immersion may result in what has been termed "Autonomic Conflict" (Tipton et al., 2010). This simultaneous stimulation of the both the parasympathetic and sympathetic branches of the autonomic nervous system results in cardiac arrhythmias (Tipton et al., 1994). In the correct set of circumstances, it is thought that the arrhythmias resulting from Autonomic Conflict may become life-threatening (Shattock and Tipton, 2012).

After the first few minutes, the CSR begins to subside due to reduced firing frequency of the cold thermoreceptors as they adapt to the cold temperature that first triggered them (Hensel, 1981). Once the CSR subsides the next phase of cold water immersion presents a different threat to survival. As cooling of the limbs occurs, swimming efficiency is significantly reduced, resulting in "swim failure" (Tipton et al., 1999). Tipton and colleagues investigated the changes in swimming performance that occur after an initial immersion, and before the onset of hypothermia. When participants swam in 10°C water, compared to 18°C and 25°C, their swimming stroke length was decreased, while stroke rate increased (Tipton et al., 1999). During the tests in 10°C water, the swimming angle of the participants also changed, with the participants becoming more upright in the water, increasing the amount of effort required to stay afloat in order to resist the additional drag and sinking force (Golden and Tipton, 2002). Near the end of the swims in 10°C water, shivering occurred in combination with swimming. The asynchronous activation of the muscles caused by shivering impaired swimming ability even further (Tipton et al., 1999). In addition, Tipton and colleagues found a correlation between the thickness of fat over the arms and swimming efficiency in their participants, and they suggest that arm cooling and resultant muscle fatigue may have been the primary mechanism that led to the decline in swimming ability (Tipton et al., 1999). The observation regarding arm cooling is supported by earlier work by Pugh who said that muscle fibers become inactive when their temperature drops below 27°C (Pugh, 1967). Pugh (1967) stated that low muscle temperatures may also be related to stiffness and cramping culminating in a reduction in maximum force output (Sargeant, 1987).

Along with the force reduction, the cooling of nerves results in a reduction in their conduction velocity (De Jong et al., 1966), leading to feelings of numbness. Within a short time, the cooling of muscle and nerves can lead to a loss of function equivalent to peripheral paralysis (Stocks et al., 2004), significantly impacting the ability to perform necessary survival tasks such as grabbing onto a lifeline if in the water. This significant reduction in the ability of the hands to perform these tasks is highlighted by accounts from the survivors of the MV *Estonia*. One survivor tried to open a survival container in a liferaft that contained a bailer. The survivor was unable to open to the package with their hands due to the loss of function, and had to resort to using their teeth (Estonia, 1997). The longer this phase of cold water immersion can be delayed the greater chances of survival for a person as they retain the necessary dexterity and mobility to self-rescue before the next threat to survival occurs.

If the initial or short term responses to cold water immersion do not result in death, the next threat to survival is hypothermia. Hypothermia is defined as a drop in deep body temperature below 35°C (RCPL, 1966). The signs and symptoms associated with falling deep body temperature are given in Figure 2.4.

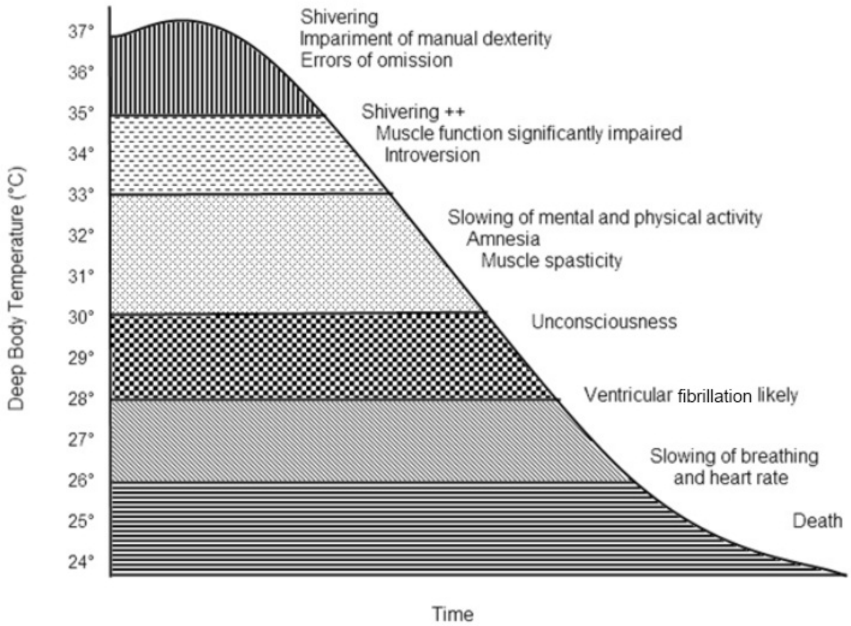

Figure 2.4. Signs and symptoms associated with falling deep body temperature (From Golden [1973] in Golden and Tipton [2002]).

In addition to the reduction of heat loss by vasoconstriction, the other thermoregulatory response seen with a drop in deep body temperature is shivering. When shivering, opposing muscles rapidly contract asynchronously resulting in little mechanical work being performed (100% inefficient), but heat is generated (Golden and Tipton, 2002). The peak shivering intensity (i.e. maximum metabolic heat generation) has been measured to be approximately five to six times resting values (Eyolfson et al., 2001), and approximately 50% of maximum oxygen consumption (Golden et al., 1979). Vasoconstriction and shivering are neurally driven and happen rapidly upon immersion in cold water (Barcroft and Edholm, 1943; Hayward and Eckerson, 1984). In contrast, it takes time for the conductive pathway for heat loss to be established due to the reduction caused by vasoconstriction and, with a rapid increase in heat production due to shivering, heat balance moves in favour of heat gain, during the initial minutes of immersions, producing an initial rise in deep body temperature (Figure 2.4).

If vasoconstriction and shivering are not sufficient to compensate for heat loss to the environment, the participant will continue to cool by conduction and convection ("forced convection" if a current is present or the victim moves) and develop hypothermia. Shivering intensity will increase as deep body temperature drops, but may eventually cease as deep body temperature continues to drop past 30°C (Burton and Edholm, 1955). Muscle rigidity will be lost once deep body temperature reaches 27°C (Alexander, 1945), at which point cardiac arrhythmias are likely which can lead to ventricular fibrillation, cardiac arrest and death (Golden, 1973).

It follows that with intense peripheral vasoconstriction and minimum blood flow to the extremities, the major path of heat loss in the body is conductive. Thus the primary area for heat loss in cold water once vasoconstriction has occurred is in the torso, specifically the back of the torso if the individual is laying on their back and compressing the external insulation of the immersion suit (Golden & Tipton, 2002).

Shivering and vasoconstriction are thermoregulatory responses to the thermal stress to delay or prevent the onset of hypothermia. Generally, the more intense the thermal stress, the more strain the thermoregulatory system experiences as it tries to compensate and prevent a drop in deep body temperature. Deep body temperature will be preserved as long as humans can remain in the "thermoregulatory zone" where the heat lost to the external environment can be reduced by vasoconstricting, and then be replaced by heat generated through shivering *i.e.* remain in thermal balance. Hypothermia will develop when the heat lost to external environment becomes uncompensable by thermoregulatory responses, thereby moving an individual outside of the thermoregulatory zone.

2.2 Survival Time Predictions.

The length of time it takes an individual to develop hypothermia can vary depending on a large number of factors, including: the environment (air or water immersion); body fat percentage (Keatinge, 1960), and insulation provided by clothing and immersion ensembles (Tikuisis, 1989). In search and rescues scenarios, it is vital to have an accurate estimation of the expected survival time (ST) of a person for the given conditions, so that decisions to discontinue a search can be based on objective data. One of the earliest survival time prediction models was developed by Molnar (Molnar, 1946). Molnar examined U.S. Navy shipwreck reports and plotted the length of time the rescued survivors were in the water at a given water temperature (Molnar, 1946). This early attempt at predicting survival time was based on the length of time survivors were in the water, and did not allow for these predictions to be modified by inputs such as body fat percentage or clothing.

The work by Molnar led to the development of more complex ST predictions and mathematical models. Models have been developed that predict ST for individuals under a variety of conditions; they are used by search and rescue forces all over the world for casualty management and contingency planning. These models range from simple ones, based on rectal temperature cooling (Hayward et al., 1975; Hayward and Eckerson, 1984), to more complex models that divide the body into segments and focus on whole-body thermoregulation (Wissler, 1985; Tikuisis, 1989). The survival time prediction model of Hayward and Eckerson is a linear extrapolation of rectal temperature cooling rate based on the measured decline in rectal temperature of 20 participants immersed in 0°C water wearing light clothing (Hayward and Eckerson, 1984). Using the mean drop in rectal temperature of $6.02°C \cdot hr^{-1}$ a predicted survival time of 81.7 min was calculated, assuming a lethal deep body temperature of 30°C. In the same study by Hayward and Eckerson, if the rate of rectal temperature decline for each participant was used to calculate their own predicted survival time, the mean time was 95.6 ± 30.7min (Hayward and Eckerson, 1984). These discrepancies in predicted survival time within the same study emphasize that the rate of cooling can vary to a large degree between people. Hayward and Eckerson also suggest, but without evidence, that immersions in wind and waves would increase heat loss and reduce the predicted survival time compared to what was measured in calm water. Their prediction was based on the assumption that in rough water participants would be active, which would result in an increase in heat loss compared to calm water (Keatinge, 1961; Hayward et al., 1975). Work by Witherspoon and colleagues has shown that heat flow increases with increased water velocity (Witherspoon et al., 1971), therefore survival times in wind and waves should be less then calm water, even if the person remains motionless, since heat flow would be greater compared to calm water.

The Hayward and Eckerson survival time calculation assumes a linear cooling rate during whole body immersions. This predictive model is simplistic, and possibly inaccurate, since it cannot be modified by factors such as body fat percentage and insulation provided by clothing. More advanced models such as those developed by Wissler do take these factors into account (Wissler, 1985). The Wissler model (Wissler, 2003) incorporates equations that were chosen so that the computer generated survival times were consistent with the survival curve developed by Molnar (Molnar, 1946). In this regard, the Wissler thermal model has been developed based on actual immersion-related incidents. As opposed to the linear cooling rate of the Hayward and Eckerson model, the Wissler model allows the probability of survival time to be continuously computed as a function of immersion time (Wissler, 2003). Interestingly, the Wissler model does not take into account the effect of sea state on the thermal state of the person, since many of the actual cases used to support the model were in seas rough enough to cause a vessel to capsize, or a person to be carried overboard (Wissler, 2003). The predicted survival time for moderate seas in the Wissler model predicts a survival time of less than one hour when deep body temperature drops below 33°C (drowning due to unconsciousness), and greater than 50 hours when it is above 36°C (Wissler, 2003). The effect of sea state in the model affects the survival time predictions based on a person becoming unconscious due to severe hypothermia and unable to avoid drowning if lacking a PFD, as opposed to taking into account the thermal effects of the environment compared to calm water. While Wissler does suggest that sea state affects the thermal state of the victim, he continues by saying that rough seas only cause a small reduction in the overall thermal resistance of the clothing worn (Wissler, 2003); this suggestion has yet to be confirmed.

Another advanced thermoregulatory model is the Cold Exposure Survival Model (CESM) developed by Tikuisis, that considers the human body as a passive heat transfer system divided into eight segments (Tikuisis, 1989). Each segment contains concentric annular compartments representing the core, muscle, fat, skin and clothing, and all compartments are assigned the thermophysical properties of heat capacity, thermal conduction, physiological values of metabolic heat production and blood flow (Tikuisis, 1989). The CESM allows for several factors to be input into the model to help further refine stochastic, or single point predicted survival times, these include: environmental conditions; anthropometrics of the casualty including level of fatigue; to what depth they are immersed; and underclothing and immersion ensembles worn (Keefe and Tikuisis, 2008). The advantage of the CESM over other models is that it can be customized to unique survival scenarios, for both air and water exposures, and is constantly evaluated and refined as more data become available (Keefe and Tikuisis, 2008). The CESM has been tested against laboratory immersions (Tikuisis, 1989) and accident cases for both air and water exposure (Tikuisis, 1995) and has provided estimations of deep body temperature for given conditions that are in good agreement with the actual/reported deep body temperature (Keefe and Tikuisis, 2008). Due to its accuracy and customization for unique scenarios, the CESM is the current model used by Canadian Search and Rescue forces for predicting the survival times of those accidentally immersed.

2.3 Thermal Manikins.

The assessments of the thermal protective properties of immersion suits are challenging tests for human participants to endure. The current Life Saving Appliances (LSA) code require human participants to perform six hour immersions in calm, circulating 2°C water (IMO, 2010). The deep body temperature of the participants is monitored in real time to ensure that hypothermia does not develop, and finger and heel temperature are measured to ensure they do not drop below the values where a non-freezing cold injury could occur (IMO, 2010). Current Canadian General Standards Board (CGSB) standards for marine abandonment suits (CGSB, 2005) and helicopter passenger transportation suits (CGSB, 1999) require similar tests to be conducted: participants perform six hour immersions in 2°C water. These kinds of tests are taxing on participants, as they are required to remain in near-freezing water for prolonged periods of time. The ethical nature of these tests has also been questioned, as participants are put through significant discomfort to determine if a suit is indeed “good enough” to delay hypothermia and help ensure rescue (Barwood and Tipton, 2011). Variability in physiological responses during immersion suit testing, and high cost and time requirements, may be the rationale for manufactures preferring an alternate method for testing.

An alternative to using participants for immersion suit certification is thermal manikins. Thermal manikins are used over the world to measure the thermal insulation of clothing ensembles in a variety of conditions. More than 100 manikins are in use worldwide (Holmer, 2004), but generally they are multi-segmented, built to the same physical dimensions as a 50th percentile male (Height: ~1.75m; SA: ~1.92m^2). Each segment contains an electric heater and is capable of being held at a set temperature. The amount of power required to maintain a segment at the preset temperature is equivalent to the heat lost to the external environment (Smallhorn, 1988). Clothing insulation values are calculated based on the amount of power required to maintain a manikin segment at a set temperature for the given environmental conditions.

Thermal manikins are viewed as a cost effective, ethical method for measuring the thermal protective properties of clothing ensembles, including immersion suits. Instead of immersing six or more participants in near-freezing water for six hours, a single manikin test can be conducted in approximately three hours in the same conditions. In terms of performance criteria, where a human must not develop hypothermia during the immersion suit tests, a thermal manikin has to measure an insulation value of 0.75clo[3]. This measurement takes into account three separate "layers" of insulation: the underclothing worn by the manikin/human; the outer layer of clothing (i.e. immersion suit); and the fluid boundary layer next to the body. When referring to a clo value in this thesis, it is taken to mean the total insulation provided by all three layers.

Given the potential benefits of using thermal manikins for certifying immersion suits, their incorporation as measurements tools in standards has been slow. The current edition of the Life Saving Appliances (LSA) code will allow the use of thermal manikins to certify immersion suits, but only after satisfactory correlations have been established between manikins and humans (IMO, 2010). The International Organization for Standardization (ISO) will only allow immersion suits to be tested with humans stating that no manikin is available giving sound test results (ISO, 2002).

Early work by Romet and colleagues compared the values of immersion clothing insulation measured on human participants and on a thermal manikin for anti-exposure suits (Romet et al., 1991). Five male participants wore a variety of clothing ensembles ranging from uninsulated anti-exposure suit ("traditional fishing attire"), to single-piece insulated immersion suits. The participants performed 30 minute immersions in 20°C still water, and then 25-40cm waves were generated in the tank for an additional 20 minutes. A Thermal Instrumented Manikin (TIM) was tested in the same environmental conditions and clothing ensembles as the participants. There

[3] 1 clo is equal to the amount of insulation required to keep a seated person comfortable in 21°C air, 50% or less relative humidity, and an air movement speed of $0.1 m \cdot s^{-1}$. 1 clo = $0.155 °C \cdot m^2 \cdot W^{-1}$.

were no statistical differences evident between the clo values for the humans and TIM in the still water conditions, but in the waves condition, TIM had significantly lower values (Romet et al., 1991). During the waves condition, the average clo values measured for the humans were about 40.9 % higher (Human mean clo: 0.19; manikin mean clo: 0.12) than those measured on TIM. For the humans, the only significant difference in segmental heat flow was on the back, which was greater in the wave condition compared to still water. In comparison, TIM showed a significantly greater increase in heat flow at the arm and abdomen sites in the wave condition compared to still water. This was attributed to the rigidity of TIM; when in waves, the arms and abdomen would enter the water and act like a scoop. The more physically compliant humans rode each wave, resulting in no scoop-like action occurring. The mean clo difference between the still and wave conditions for humans was 29.7% (mean calm clo: 0.27; mean turbulent clo: 0.19); while for TIM it was 56.7% (mean calm clo: 0.26; mean turbulent clo: 0.12) (Romet et al., 1991). Romet and colleagues conclude that while obvious differences exist between TIM and humans, the former erred on the side of safety and over-estimated heat loss in the wave conditions. They suggest that thermal manikins are excellent devices for testing in still water, but that more research is required to make them applicable for testing in turbulent conditions (Romet et al., 1991).

Romet and colleagues found no statistical difference in clo values between the humans and manikins in the still water condition in their study, but the warm temperature of the water (~20°C) may have been a limiting factor. As discussed previously, as a human cools an early thermoregulatory response is vasoconstriction which reduces peripheral blood flow leading to a fall in skin temperature (Barcroft and Edholm, 1943). Later work by Tipton and Balmi investigated the effect of varying amounts of water leakage underneath uninsulated immersions suits in 10°C water (Tipton and Balmi, 1996). Twelve male participants performed immersions while wearing swimming trunks; long-legged and long sleeved cotton underwear; woolen socks; a knitted woolen ankle to neck insulating garment (“Woolly bear”); and an uninsulated immersion suit. Tested alongside the participants was a Thermal Instrumented Manikin (TIM); the same manikin used in the previous study by Romet and colleagues (Romet et al., 1991), and currently used in the certification process for immersion suits in Canada. Varying amounts of water (0L, 0.2L, 0.5L and 1L) were applied in a standardized manner underneath the immersion suits, over the torso to simulate water leakage. A separate test condition where 0.5L was applied over just the limbs was also undertaken. Tipton and Balmi found that 0.5L and 1.0L of water applied over the torso of humans caused a significantly greater fall in deep body temperature compared to the 0L, and 0.2L conditions, and to the condition where 0.5L was applied over the limbs. Interestingly, there was no significant difference in the rate of fall of deep body temperature between the 0L condition (dry) and 0.5L over the limbs. They concluded that the location of the water leakage was as important as the amount, since 0.5L over the torso caused a significantly greater rate of fall of deep body temperature than when the same volume was applied over the limbs (Tipton and Balmi, 1996). As a result of vasoconstriction, the participants in Tipton and Balmi's study were able to reduce the amount of blood flow to their extremities, reducing the amount of heat lost in this region and reduce the impact of limb wetting.

TIM was tested alongside the participants in Tipton and Balmi's study and had the same amount of water leakage applied underneath the immersion suit. When 0.5L of water was applied over the limbs of TIM a greater reduction in clothing insulation was measured compared to when the same amount was applied over the torso (Tipton and Balmi, 1996). Tipton and Balmi state that on a manikin, a leak over the limbs has a greater detrimental effect compared to an equivalent leak over the torso; the opposite effect as that measured with the human participants. This was attributed to thermal manikins being unable to vasoconstrict; rather they hold a set temperature for each regional segment. Due to the cylindrical shape of the limbs they have a much higher surface area to volume ratio in this region compared to the torso, this results in a much greater amount of heat flow. A manikin does not thermoregulate, and as a result will continue to maintain a set temperature in the limbs regardless of immersion conditions and duration. As Tipton and Balmi stated, if thermal manikins are used to evaluate the thermal protective properties of immersion suits, through a "natural selection" process an immersion suit may be chosen that will benefit a manikin more than a human i.e. more relative insulation on the limbs than the torso (Tipton and Balmi, 1996). However, more insulation over the torso is more beneficial to humans as the insulation will work in tandem with the human thermoregulatory system that will reduce heat loss through the limbs. Humans would gain little benefit from increased insulation over the limbs since the greatest region of heat loss is from the torso, especially the back due to hydrostatic compression of the under clothing and suit insulation (Tipton and Balmi, 1996).

Where immersion suit insulation should be concentrated is an important consideration, especially for helicopter passenger transportation immersion suits. Unlike marine abandonment suits, helicopter passenger transportation immersion suits have a maximum allowed buoyancy of 175N (CGSB, 1999) in order to ensure that an individual can escape from a submerged helicopter. Since insulative material adds to the overall buoyancy of a suit, a compromise exists between trying to ensure that a sufficient amount of buoyancy is distributed to provide thermal protection, but not too much that the suit becomes cumbersome and too buoyant. Through the "natural selection" process described by Tipton and Balmi, a suit may be designed with more insulation over the limbs since that would give the best performance in thermal manikin tests, but would prove to be of little benefit to humans. To date, no standard in the world takes into account this disparity between manikins and humans and the importance of the location of a leak for the consequences on deep body temperature and survival time. As discussed in the next section, certain standards allow the use of thermal manikins, but only require an overall clo value to be achieved, while others will only allow the use of manikins once satisfactory correlations are achieved with humans. Caution should be exercised when using thermal manikins in certification process outlined in standards in order to ensure that the immersion suit designs they inevitably drive benefit the humans who use them, and not the manikins that test them.

2.4 Immersion Suit Standards.

2.4.1 Canadian General Standards Board.

Currently, Canada is the only country in the world where the preferred method of certifying the thermal protective properties is using a thermal manikin for both standards: Marine Abandonment Suits (CAN/CGSB-65.16-2005); and Helicopter Passenger Transportation Suit Systems (CAN/CGSB-65.17-2012).

Both Canadian standards assume that water leakage into an immersion suit *will* happen, and build in safety factors to account for this assumption; this requirement makes the standard more reflective of the real life scenario. The leakage tests in CAN/CGSB-65.16-2005 require that both a 3m jump, or higher, and a one hour swim tests in calm water are conducted. Once the tests are completed, the values used to calculate the water ingress for both the jump and swim tests are to be one standard deviation above the mean for the results from 11 participants (CGSB, 2005). The values from the one hour swim are then multiplied by three (to give an estimated water ingress after three hours of swimming), and added to the jump test water ingress to give the total ingress for the suit, which is then added before the start of the thermal insulation test. Using one standard deviation above the mean as the calculated value helps to create a safety factor by over reporting the average water leakage for the 11 participants.

CAN/CGSB-65.17-2012 includes a different leakage test compared to the 3m jump and swim test in calm water in CAN/CGSB-65.16-2005. Instead of a jump test, participants escape from a submerged helicopter simulator, and then perform survival actions (swimming away from submerged helicopter, then boarding a liferaft) in wind and wave conditions (CGSB, 2012). Water leakage accumulated during these actions is recorded, and then the participants perform a one hour immersion in wind and waves. Water leakage into the suit is measured halfway through the immersion (30 min mark) and again at the end.

For both standards, the amount of water ingress recorded during the leakage tests is added to the immersion suit prior to the beginning of the thermal test. If the suit passes the thermal protective tests with the specific amount of water underneath the immersion suit, then this amount is considered an acceptable amount of water leakage.

Both standards allow the thermal protective tests of the immersion suits to be established using either human participants or a thermal manikin. The thermal protective tests using human participants are different between the two standards. For CAN/CGSB-65.16-2005, if using human participants, then at least four males and four females must be studied. The participants dress in wool socks, cotton undershirt, cotton underwear, cotton pants (CAN/CGSB-65.16-2005) and a long sleeve shirt. The amount of water ingress measured during the leakage tests is then added underneath the immersion suits. Participants perform a six hour immersion in 0-2°C calm, circulating water while rectal, finger, and toe temperatures are measured. The test is terminated if: the rectal temperature of the participants drops 2°C below pre-immersion values; finger or toe temperature drops below 8°C for more than 15 minutes; the participant requests the immersion to end; or the attending physician present determines the test should not continue (CGSB, 2005). If none of these termination criteria occur the immersion suit passes the thermal protective test using humans.

In CAN/CGSB-65.17-2012, the thermal protective tests using human participants have been changed, and the test conditions have been made more challenging by the inclusion of 20-25cm waves, and $7m \cdot s^{-1}$ winds during the six hour immersions (CGSB, 2012). Instead of wearing the same underclothing ensemble as in CAN/CGSB-65.16-2005, participants now wear cotton socks, cotton underwear, cotton t-shirt and standard weight, uninsulated long-sleeve coveralls.

The alternative to using human participants for the thermal protective tests is using a thermal manikin. Contrary to the human tests, the thermal protective tests using thermal manikins are the same in both CGSB standards. The thermal manikin is dressed in the same underclothing ensemble as worn by the human participants, and the measured water leakage is added underneath the immersion suit. However, the manikin performs immersions in 40cm waves, compared to the calm circulating water that the human participants are tested in for marine abandonment suits (CAN/CGSB-65.16-2005), and the 20-20cm wave and $7m \cdot s^{-1}$ wind for helicopter passenger transportation suits (CAN/CGSB-65.17-2012). If the thermal manikin measures an overall clothing insulation value of at least 0.75clo, the immersion suit passes the thermal protective test.

2.4.2 International Organization for Standardization (ISO).

The International Organization for Standardization (ISO) has similar tests to the Canadian standards with regards to water leakage and thermal protection. Participants are dressed in the same clothing ensemble as specified in the Canadian standards. For the leakage tests, participants perform a jump from 4.5m in height, and then swim for 20 minutes in calm circulating water (ISO, 2002). Similar to the Canadian standards, the amount of water ingress is recorded; this is added at the start of the thermal protective tests. For insulated immersion suits, the participants perform a six hour immersion in 0-2°C calm, circulating water with an air temperature less than 10°C. If the participants do not develop hypothermia, the insulated immersion suit passes the thermal protective tests.

Compared to the Canadian standards, ISO tests are not as rigorous due to the lower volume of water added in the leakage test. Where the Canadian standards overestimate water leakage by taking one standard deviation above the mean measured water ingress; ISO only requires the mean water ingress. The increased water ingress in the Canadian standard adds in a safety buffer resulting in a more rigorous thermal protective test.

An interesting difference to note between the Canadian and ISO standards is with regards to thermal manikins. ISO states "…….that for the time being no manikin is available giving sound test results. Therefore the performance of a suit system has to be proved by tests with human subjects. As soon as a manikin showing a sound performance [is identified] the testing laboratories have the option to go forward and choose one of [or] both methods" (ISO, 2002).

2.4.3 International Maritime Organization (IMO) – Life Saving Appliances 2010 Edition.

The water leakage and thermal protective tests prescribed in the IMO standards are very similar to those of ISO. For the water leakage tests, participants jump from a height that is sufficient to completely immerse them, and the ingress of water should not exceed 500g (IMO, 2010). The leak test can be accomplished by one of two methods: 1. A one hour immersion in calm water, or 2. Swimming for 20 min for a distance of at least 200m (IMO, 2010). Following this second test, there should be no more than 200g of water ingress into the immersion suit.

Similar to both the CGSB and ISO, the amount of water measured during the leakage test is added underneath the immersion suit before the thermal protective tests. The underclothing worn by the participants is the same as in CGSB and ISO. The test conditions and criteria are also the same as well: prevent a 2°C drop in deep body temperature in six hours in 0-2°C calm, circulating water (IMO, 2010).

2.4.4 European Aviation Safety Agency (EASA).

The European Aviation Safety Agency (EASA, 2006) standard for immersion suits heavily references the ISO standards for leakage and thermal protective tests. For the water leakage tests, the EASA standard references ISO 15027-3:2002, but states that no more than 200g of water shall leak into the immersion suit (EASA, 2006). For the thermal protective tests, the EASA states that the immersion suit shall at least satisfy the test requirements as outlined in ISO 15027-3:2002 as a Class B Suit (EASA, 2006).

2.4.5 Civil Aviation Authority United Kingdom Specification No. 19 – Helicopter Crew Member Immersion Suits.

The leakage tests outlined the UK standard are similar to those outlined in ISO and Canadian standards, but state that no more than 200g of water should leak into the immersion suit (UKCAA, 1991). Interestingly, there is no proposed test in the UK for measuring thermal protection. Instead it is stated that if the suit allows less than 200g of water into it (and the person is wearing an underclothing ensemble of a similar insulation value to cotton underwear, long sleeved heavy cotton shirt, cotton pants, wool socks, and a military type long sleeved pullover), then the suit will provide the wearer with three hours protection against hypothermia when immersed (UKCAA, 1991).

2.4.6 The Norwegian Oil Industry Association (OLF).

This standard is similar to the EASA standard in that it often refers back to ISO 15027-3:2002 for test protocols. It differs from the EASA standard by requiring more stringent testing conditions. The OLF requires that leakage tests be performed as outlined in 15027-3:2002, but that no more than 200g of water enter the suit. The thermal protection tests are also conducted according to 15027-3:2002, but are made more thermally demanding by adding $5 m \cdot s^{-1}$ wind, and pouring water over the front of the body every 10 minutes (OLF, 2004).

The thermal protective tests outlined in the different standards over the world focus on preventing hypothermia from occurring in participants wearing the immersion suits. Previous work by Hayward (1984) has shown the effectiveness of immersion suits in preventing hypothermia. Thirty male participants performed six hour immersions in 1°C stirred water while wearing five separate dry, insulated commercially available immersion suits. Underneath the immersion suits, participants wore a clothing ensemble similar to those prescribed by the various testing standards. During the six hour immersions, the mean fall in rectal temperature was approximately 0.8°C. In a separate study by Hayward and Eckerson (1984) participants, wearing a similar clothing ensemble to the previous study, were immersed in 0°C water but without immersion dry suits. When this group of 10 males and 10 females performed immersions in the same temperature water as the other group that wore immersion suits, their rectal temperature fell 2°C in 30 minutes (Hayward and Eckerson, 1984). While the two studies used different groups of participants, the large difference in rectal temperature cooling rates between the two ($6.0°C \cdot hr^{-1}$ for no immersion suit; $0.13°C \cdot hr^{-1}$ for immersion suits) show how effective immersion suits can be in slowing the development of hypothermia in near freezing water.

2.5 Immersions in Wind and Waves.

Recent maritime accidents, such as the *Check Mate III* sinking and crash of Cougar flight 491, have called into question how effective immersion suits are in conditions outside of a controlled laboratory setting. Many standards over the world require that immersion suits prevent hypothermia from occurring in six hours, yet in these accidents individuals have died, or had extremely low deep body temperatures, in about a third of that time.

Previous work has examined the change in performance of immersion suits when immersed in conditions more representative of being offshore (e.g. wind and waves) compared to the calm water trials that are often prescribed in standards. Hayes and colleagues examined the effect that wave action had on eight male participants who wore a variety of clothing ensembles (Hayes et al., 1985). The immersion time for the participants ranged from one to four hours depending on the clothing ensemble worn. Participants wore a variety of clothing ensembles, ranging from swimming trunks and a lifejacket, up to an ensemble that consisted of: long underwear;

undercoverall, ‘immersion undercoverall’, boots, socks, gloves, flight suit, helmet, and life jacket. The water temperature varied according to the clothing ensemble worn, with the highest temperature being 28.4°C when in swimming trunks, and the lowest being 7.3°C when wearing the ensemble with the flight suit (Hayes et al., 1985). The two immersion conditions were calm water, and in waves which had an “aggravated lop” of approximately 0.3m (0.6m in height). Hayes and colleagues found that in 8 out of the 10 cases, the rate of fall of rectal temperature was not significantly higher in waves compared to calm (Hayes et al., 1985). They state that the effect of waves is more evident when nude or wearing little clothing, and that with the immersion suit ensembles, it is the neck/face seals that are consistently challenged in waves. If the seals on the immersion suit fail, the leaking and flushing of water into the suits could be the major difference between immersion in calm water and waves (Hayes et al., 1985). Hayes and colleagues conclude that their preliminary study demonstrated a trend for waves to increase cooling in some cases, but they state that more definitive experimentation is required (Hayes et al., 1985).

A more detailed study was conducted by Steinman and colleagues a short time later in which eight participants wearing a variety of clothing ensembles performed immersions in both calm water and rough seas (Steinman et al., 1987). The clothing ensembles included: the control ensemble (flight suit, flight helmet, flight boots with wool socks, flight gloves, cotton thermal underwear, and inflatable life-vest); 3.2mm Neoprene wet suits; insulated immersion suits with cotton underwear and socks worn underneath. All immersions for this study were conducted in the mouth of a river. The water temperature during the calm water tests was approximately 10°C; air temperature was 12°C with a wind speed of 2.5 – 5.0$m \cdot s^{-1}$. For the rough water tests, a 13.2m motorized lifeboat was used to create swells and breaking waves, and the wake produced by a 5.1m rigid hull inflatable boat was used to create chop (Steinman et al., 1987). The water temperature during the rough conditions was 11°C with 1-2m swells, 0.5m chop, and occasional 1.5m breaking waves. Air temperature was 12°C with a wind speed of 5.0 – 10.0$m \cdot s^{-1}$.

Steinman and colleagues found that for the majority of the clothing ensembles tested, the rate of rectal temperature decrease was significantly greater in the rough condition compared to calm water (Steinman et al., 1987). An interesting finding was that for one of the two immersion suits tested, the rate of rectal temperature decrease was significantly greater in *calm water* compared to rough water. However, this could be explained by the fact that Steinman and colleagues noted that participants had to actively work (tread water/exercise), to maintain their posture in the rough seas conditions. They believe that due to this physical exertion (indicated by increased heart rate), metabolic heat production was greater in the rough condition compared to calm. If this is indeed the case, then any increased cooling effect caused by the rough conditions may have been masked by the increased heat production. $\dot{V}O_2$ was not measured in the study, so there is no direct way to confirm this. Steinman and colleagues state that the increased cooling rates seen in the rough conditions when the participants wore "wet" anti-exposure suits is due to wave action flushing away the warmer boundary layer of water trapped between the suit and skin. With this boundary layer being constantly displaced due to wave action, the "wet" anti-exposure suits, convective heat flow will have increased compared to calm water immersions (Steinman et al., 1987). Even though rectal temperature declined in one style of immersion dry suit and not the other, the study authors suggest that wave action may challenge immersion suit seals. Similar to the ideas postulated by Hayes and colleagues, Steinman and colleagues believe that increased wave action may result in the water penetrating immersion suit seals, leading to increased leakage into the immersion suit. An increase in water leakage due to wave motion would result in faster cooling compared to calm water due to the reduction in underclothing insulation.

Later work by Tipton examined the effect that wind, waves, and periodic surface spraying had on human thermal responses (Tipton, 1991). Participants performed immersions wearing an uninsulated immersion dry suit in two separate conditions: calm water and in 15cm waves, $3 m \cdot s^{-1}$ wind with periodic spraying of water (simulated rain). The water temperature in both conditions was 4°C. Tipton found that even in the relatively mild environmental conditions tested, the inclusion of wind, waves, and spray resulted in a 30% reduction in predicted survival time compared to calm water (Tipton, 1991). In a subsequent paper, Tipton states the need for standards test to be undertaken in conditions representative of those that may occur during an accident, or performance may be over estimated as a result. This would result in what Tipton describes as "unexpected poor performance" of immersion suit during an accident (Tipton, 1995). Interestingly, Tipton notes that while "surprisingly poor performance" should not occur, "surprisingly good performance" should not occur either, since the immersion suit should work the way it is expected to. If facilities that can recreate the wind and wave conditions found in open water are not accessible to ensure an accurate assessment of performance, a correction factor could be determined for the decrement seen in such conditions (Tipton, 1995).

The studies described thus far have reported on the effect that rough weather conditions have on human thermal responses, but were all conducted with only one specific wave height. A study by Ducharme and Brooks investigated the effect that varying wave heights had on the heat loss from six participants (Ducharme and Brooks, 1998). The participants wore a wool one-piece undergarment and socks underneath an uninsulated, immersion dry suit. The participants performed one hour immersions in 16°C water, in wave heights ranging from calm water to 70cm in height in 10cm increments. Ducharme and Brooks found no significant change in rectal temperature across wave heights, but given the temperature of the water and short immersion duration, this was to be expected (Ducharme and Brooks, 1998). Ducharme and Brooks did find that the total thermal resistance of the immersion dry suit, as measured by the heat flow from the participants, was decreased during wave motion compared to still water. They found that mean skin heat flow at wave heights of 10 and 20cm was not significantly different from that measured in calm water (Ducharme and Brooks, 1998). Mean skin heat flow was significantly greater, compared to calm water, at wave heights 30cm and higher. This suggests that waves of a minimum height of 30cm are required to alter heat flow significantly compared to calm water. Similar to the findings of previous authors, Ducharme and Brooks suggest that three factors could contribute to the reduction of insulation provided by a dry suit: 1. water leakage, 2. compression of suit insulation by the wave motion, and 3. reduction of the water and air boundary layer due to water movement.

Hall and Polte examined reduction of suit insulation by hydrostatic compression (Hall and Polte, 1956). A copper thermal manikin wearing a clothing ensemble that consisted of insulated garments underneath an anti-exposure suit was immersed up to the neck. Compared to values measured while in air, immersion up to the neck level resulted in a 56% reduction in insulation (Hall and Polte, 1956). The neck level immersions performed with the manikin in the Hall and Polte study is not entirely representative of the normal supine floating position assumed by an individual when in the water. As a result, the reduction in suit insulation due to compression will be less when a person is floating horizontally in the water, compared to being immersed up to the neck. In addition to the neck level immersions with the thermal manikin, Hall and Polte also measured the effect that varying levels of wetness had on insulation. When immersed in the water, 684g of water added underneath the immersion suit to simulate water leakage resulted in a drop in total insulation by 27.5%; 1986g of water resulted in a reduction of 49.6% (Hall and Polte, 1956).

The reduction in insulation values reported by Hall and Polte (1956) were also supported by a later study conducted by Allan and colleagues (Allan et al., 1985). They found that when 500g of water was added underneath an uninsulated immersion suit worn by a thermal manikin, the mean reduction in total insulation was approximately 30% for the three different clothing ensembles worn (Allan et al., 1985). When 2000g of water was added, the mean reduction in total insulation was approximately 54% (Allan et al., 1985). The reduction in total insulation for these water amounts (500g – 30%; 2000g – 54%) was similar to those reported by Hall and Polte (1956). Building upon the work by Allan and colleagues, Light and colleagues found that 500g of water underneath an immersion suit would reduce predicted survival time to an average of 1.7 hours compared to 3.5 hours when dry (Light et al., 1987). Tipton and Balmi have shown that not only is the amount of water leakage important, but where the leakage occurs is also important (Tipton and Balmi, 1996). Five hundred grams of water applied over the torso of humans caused a significantly faster fall in deep body temperature compared with no water leakage, but when 500g of water was applied over the limbs the rate of change in deep body temperature was not significantly different compared to when they were dry (Tipton and Balmi, 1996).

Table 2.1 provides a summary of the results of select studies that examined the thermoregulatory responses of participants in various immersion ensembles in different environmental conditions. As is evident from the table, very few studies have been conducted whilst manipulating environmental conditions in a repeatable, controlled way. The results from these studies suggest that a combination of colder water temperatures (< 10°C) and clothing ensembles with low insulation values are more likely to decrease deep body temperature in wind and waves compared to calm water. Further studies that repeatedly produce environmental conditions similar to those found at sea would make important contributions to addressing the disparity between thermal responses of immersed humans in calm water, and in wind and waves.

Table 2.1. Summary of results from select studies that examined thermoregulatory responses in different environmental conditions.

Study	T_W (°C)	Immersion Ensembles	Waves	Wind	Significant Increase in MSHF?	Significant Decrease in T_{DB}?
Hayward (1984)	1.0	Insulated immersion dry suits	No	No	Not measured	No
Hayes et al. (1985)	7.3 - 30.5	Nude; light clothing; flight suits.	Yes	No	Not measured	No
Steinman et al. (1987)	10.7 – 11.1	Variety – ranged from flight suits to immersion dry suits.	Yes	Yes	Not measured	Yes for: float coats; air/boat crew coveralls; full wet suits; immersion suit (one brand)
Tipton (1991)	4.0	Uninsulated immersion dry suits (two brands)	Yes	Yes	Not measured	Yes for one brand of immersion suit
Ducharme and Brooks (1998)	16.0	Uninsulated immersion dry suits	Yes	No	Yes (waves 30cm and higher)	No

Immersion suit standards all over the world often prescribe that the thermal protective properties of immersion suits be tested in calm, circulating water; conditions not representative of where they will be used. To date, the literature appears equivocal as to whether or not immersions in wind and waves will reduce predicted survival time compared to those seen in calm water. Several studies suggest that rougher conditions will challenge immersion suit seals, resulting in greater water ingress compared to calm water, and it is this leakage that reduces survival time (Steinman et al., 1987; Tipton, 1991). Other studies suggest that rough weather conditions will also increase heat flow to the environment, compared to calm water, even without any water ingress under the immersion suit (Ducharme and Brooks, 1998). In these conditions, where no water ingress occurs, wave action flushes away the boundary layer of water next to the body, resulting in increased heat loss through convection (Witherspoon et al., 1971). The loss of the boundary layer will reduce the total clo value since it removes one of the three insulating layers (the boundary layer) contributing to the total insulation value. Other studies have suggested that the increase in physical activity required in rough conditions helps to maintain deep body temperature as the heat produced outweighs the additional heat loss associated with activity (Waag et al., 1995). Indeed, periodic lower body exercise has been advocated as a strategy to maintain deep body temperature during immersion in cold water (Faverik et al., 2010).

It seems clear, that whether or not wind, waves and any consequent increase in heat loss and metabolic rate results in an increase or decrease in deep body temperature is determined by circumstance and the clothing worn. In response to these disparate findings, a series of experiments were proposed to quantify the effect that wind and waves have on heat flow on human participants wearing current immersion protective clothing. The data obtained were compared with that measured on an immersion thermal manikin.

2.6 General Hypothesis.

It was hypothesized that:

H_1: Due to increased convective heat loss, immersions in conditions that include wind and waves will result in a significantly faster fall in deep body temperature, and therefore reduced predicted survival time, compared to that seen in calm water.

Chapter 3 - General Methods

The studies described in Chapters Four to Six investigated the change in human thermoregulatory responses when moving from calm water to environments with wind and waves. The National Research Council of Canada's Research Ethics Board (REB) approved the protocols for each study.

3.1 Participants.

3.1.1 Medical Criteria.

Males and females were recruited for Study 1. Participants were asked to complete a medical history questionnaire to determine their eligibility for the study. Volunteers who had pre-existing cardiovascular, respiratory or gastro-intestinal conditions were excluded from the study. Volunteers who had pre-existing cold induced injuries, or had recent prolonged exposure to cold environments were also excluded from the study. For Studies 2 and 3, a medical doctor examined all potential participants to determine if they were physically fit to participate. Due to the limitations with the equipment used to manage urination during the tests, only males were recruited for Studies 2 and 3.

3.1.2 Dietary Considerations.

For all studies, participants were instructed to abstain from alcohol the night before a test, to eat a normal meal 1-5 hours before arriving at the facility, and not consume caffeinated beverages at least three hours preceding testing.

3.1.3 Participant Anthropometrics.

The height of the participants was recorded once during each study, usually during their first visit to the facility, using a wall mounted tape measure (Stanley Tools Canada, Oakville, ON, CA). The mass of the participant was measured prior to the start of every test, and body fat percentage was determined using a bioelectrical impedance scale (Tanita Corporation, Arlington Heights, IL, USA). Skin fold thickness at four sites (biceps, triceps, sub-scapular, and iliac crest) was measured once during each study using skin fold calipers (Beta Technology, Santa Cruz, CA, USA) to calculate body fat percentage using the Durnin and Womersley method (Durnin and Womersley, 1974).

3.2 Immersion Conditions.

3.2.1 Offshore Engineering Basin.

All tests were conducted in the Offshore Engineering Basin (OEB) located at the National Research Council of Canada – Institute for Ocean Technology (NRC-IOT). The OEB is a 75m long, 25m wide, 2.8m deep pool with electrically powered hydraulic wave makers located on two sides (Figure 3.1).

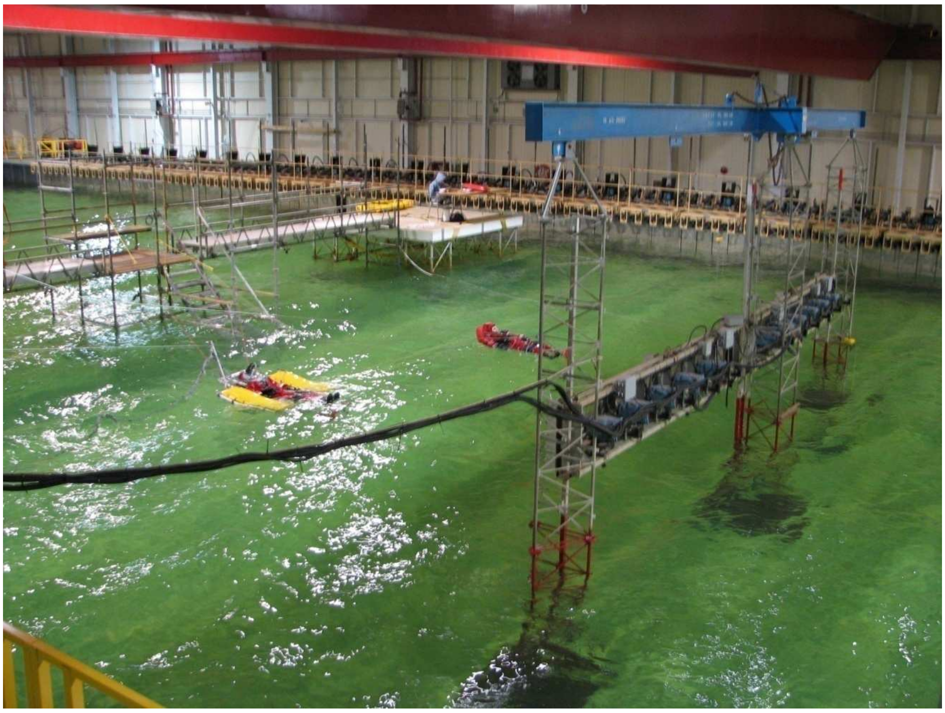

Figure 3.1. OEB located at NRC-IOT.

3.2.2 Water and Air Temperature.

The OEB does not have the capability to control water and air temperature. In order to test in water less than 15°C (Transport Canada definition of cold water), all three studies were conducted at the same time of the year: March – April. The water used to fill the OEB was taken from the municipal drinking source, with water temperature at its nadir of approximately 5°C between March and April. During each study, the OEB was periodically drained and refilled with water in order to maintain a stable temperature throughout all the tests. To help control the air temperature, all heaters in the OEB were turned off during each study. With the heaters turned off, the large volume of cold water in the OEB helped to stabilize the air temperature throughout the studies.

3.2.3 Waves.

The OEB is capable of generating waves from two sides of the basin: West and South. For all studies the waves were generated using electronically powered, hydraulic wave makers located on the west wall of the OEB. A wave absorbing beach was located on the east end of the OEB that dispersed the generated waves and reduced reflection (Figure 3.2).

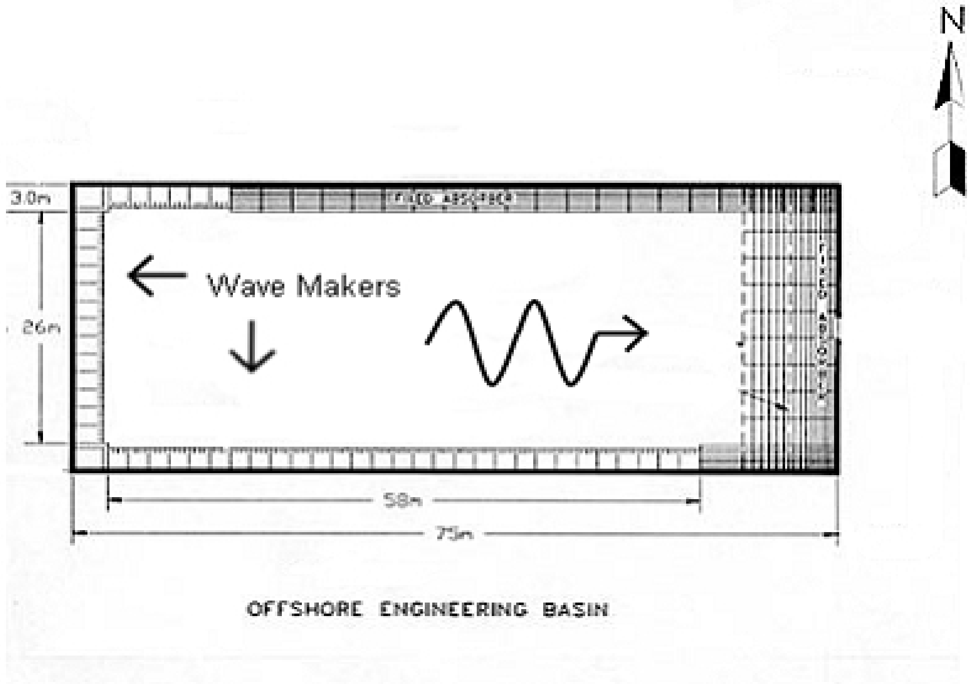

Figure 3.2. Wave generation directions in the OEB. Waves were generated using only the west side wave makers for the current studies.

A 20 minute, irregular Joint North Sea Wave Analysis Project (JONSWAP) wave spectrum was used in all three studies. The wave spectrum was generated from data collected in January 2008 from a wave buoy deployed off the south east coast of Newfoundland, Canada. This wave spectrum was truncated for two reasons: firstly, the spectrum contained waves with a very long period resulting in a very large wave length. These long period waves would produce more of a swell action (gradual rise and fall of the water) relative to the average height of the participants. Secondly, the OEB is capable of generating waves up to a maximum height of 0.9m and the spectrum generated contained waves with heights up to 5m. The spectrum was truncated to the point where it could be generated by the wave makers in the OEB. The maximum wave heights used in each study are given in Table 3.1.

Table 3.1. Maximum wave heights used in each study

	Study 1		Study 2		Study 3	
	Waves	**Wind + Waves**	**Weather 1**	**Weather 2**	**Weather 1**	**Weather 2**
Max Wave Height (m)	0.67	0.67	0.34	0.67	0.34	0.67

3.2.4 Wind.

For all three studies, 11 analog controlled custom built fans generated air flow (SEA LTD, Columbus, Ohio, USA). An OEB operator used a universal power source to control the voltage to the fans, thereby regulating the wind speed. Prior to any participants starting the tests, wind speeds were calibrated using two separate propeller type, wind anemometers (R.M. Young Company, Traverse City, Michigan, USA). The wind anemometers were calibrated using an anemometer drive (R.M. Young Company, Traverse City, Michigan, USA). One anemometer was placed in the location where the participant would be during the test, and the other was mounted on the scaffolding system behind it (Figure 3.3). The OEB operator increased the voltage to the wind machines in single volt increments for one minute in duration. Wind speed at the location of the participant versus voltage was plotted and the voltage required to achieve the desired wind speed was calculated. The anemometer at the location of the participant was then removed. The second anemometer, mounted on the scaffolding, was used to verify the correct wind speed during the tests (Figures 3.3 and 3.4)

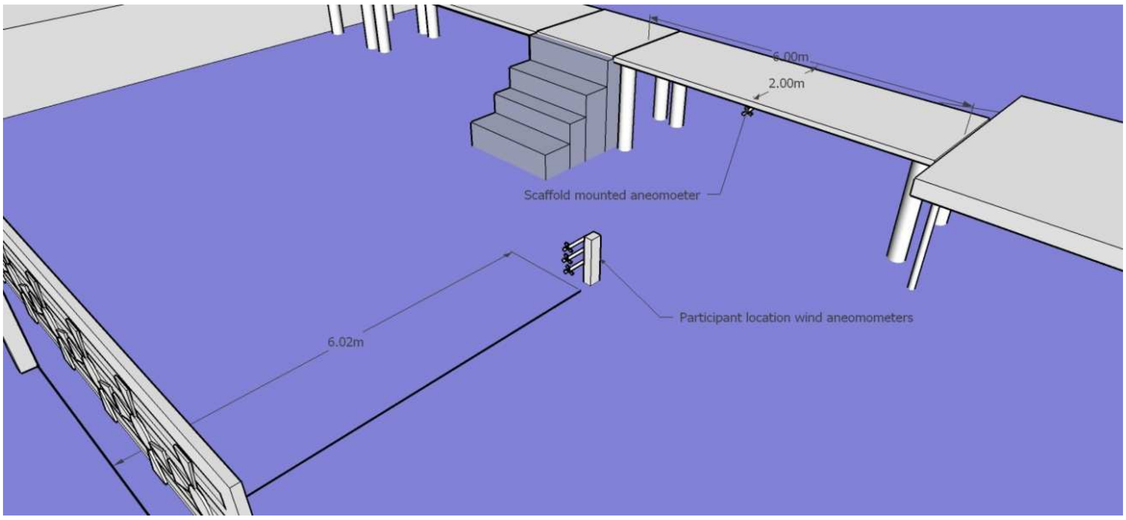

Figure 3.3. Wind anemometer locations during wind field calibration

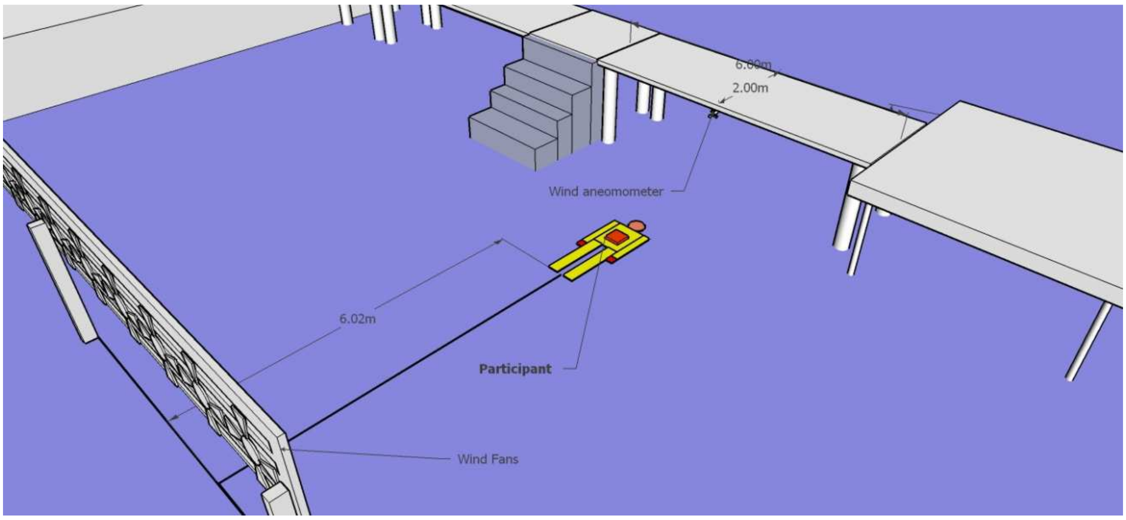

Figure 3.4. Wind anemometer location during tests with participants

3.2.5 Participant Entertainment

For Studies 2 and 3, a movie screen comprised of white pressboard and wooden planks was erected above the fans at an optimal viewing angle for the participants. The movies selected by the participant were projected onto the screen by a projector located on the north beach of the OEB (Figure 3.5). Participants wore sound reducing ear bud style headphones connected to a FM walkman contained inside the immersion suit. An FM transmitter (Decade Transmitters, Sherbrooke, Quebec, Canada) transmitted the audio for the movies.

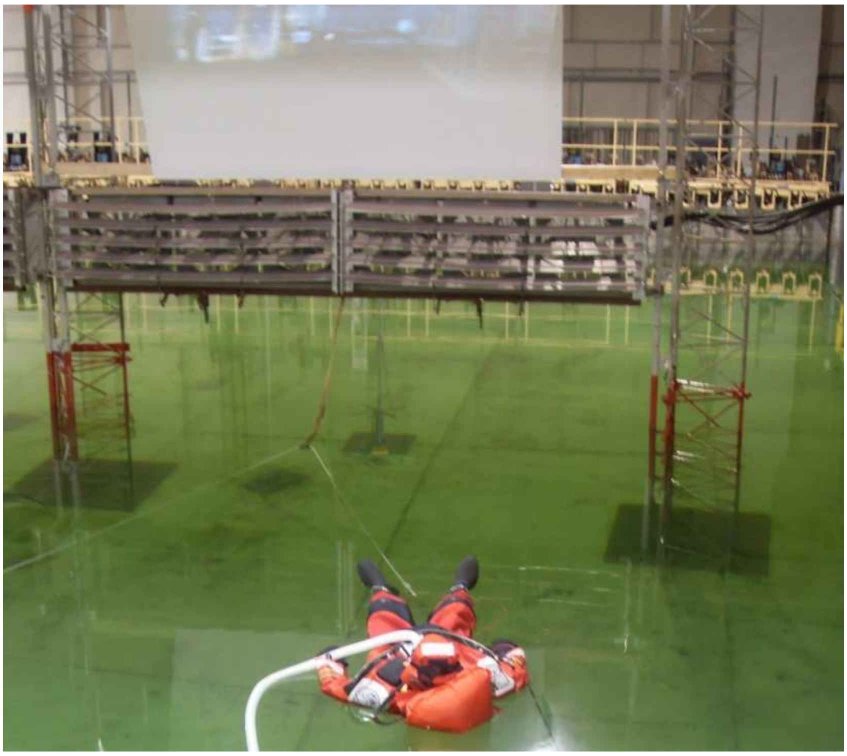

Figure 3.5. Typical calm water test undertaken in Studies 2 and 3.

3.3 Instrumentation.

3.3.1 Skin Temperature and Heat Flow.

For all three studies, skin temperature and heat flow were measured using heat flow transducers (Concept Engineering, Old Saybrook, Connecticut, USA) attached using 3M "Transpore" porous, adhesive tape to the following locations: right foot, left shin, right quadriceps, left abdominal, right pectoral, underside of right forearm, forehead, right calf, left hamstring, right lower back, left shoulder, topside of left forearm. These sites were chosen based on a similar protocol used by Ducharme and Brooks (Ducharme and Brooks, 1998), which was similar to the Hardy and Dubois modified 12 point system (Hardy and DuBois, 1938).

The values reported by the skin temperature sensors where measured against a reference probe (Automatic Systems Laboratories, Surrey, UK) in a stirred water bath (Thermo Scientific, Ashville, North Carolina, USA) set to temperatures ranging from 5-40°C, in 5°C increments. Heat flow transducer calibration constants were not checked prior to the start of the each study. After the end of the three studies, the heat flow transducers were sent back to the manufacturer to have their calibration constants rechecked. The largest variation between the original calibration prior to the start of Study 1, and after Study 3, was 2.16$W \cdot m^{-2}$ (4%).

The heat flow transducers were connected to self-contained data loggers (ACR Data Systems, Surrey, British Columbia, Canada) that measured and recorded all 12 sensors once every eight seconds. The internal memory of the data loggers was cleared prior to the start of every test, and all information was downloaded immediately after each test was completed.

3.3.2 Deep Body Temperature.

For all three studies, gastro-intestinal temperature (T_{GI}) was measured using ingestible, disposable, radio telemetry pills (HQ Inc., Palmetto, Florida, USA). Telemetry from the pills was measured and recorded once every 20 seconds by a data recorder (HQ Inc. Palmetto, Florida, USA). The pill data recorder wirelessly transmitted T_{GI} and to a shore based laptop to allow for real time monitoring of the deep body temperature of the participants. Prior to the start of each study, the data recorders were sent back to the manufacturer for a factory recalibration.

3.3.3 Respiratory Measurements.

Rates of ventilation ($\dot{V}e$), oxygen consumption ($\dot{V}O_2$), and carbon dioxide production ($\dot{V}CO_2$) were measured in Studies 2 and 3 (Cardio Coach CO_2, KORR Medical Technologies, Salt Lake City, UT, USA). Participants wore a disposable latex mask that contained two one-way valves.

The masks were secured to the participants by nylon mesh straps that could be adjusted to allow for a proper fit for each person. The mask was connected to the metabolic cart by 12m plastic tubing that was constructed from multiple 2m lengths of plastic tubes manufactured by KORR Medical Technologies. The tubes were connected together by joints manufactured by KORR Medical Technologies, and sealed using self-vulcanizing tape. Prior to the start of Studies 2 and 3, the Cardio Coach was sent back to the manufacturer for a factory recalibration. Before the start of each immersion (and approximately every 30 minutes during) the Cardio Coach would perform a self calibration by comparing itself to room air.

3.4 Immersion Suit.

For all three studies, participants wore a marine abandonment immersion suit (White's Manufacturing, Victoria, BC, Canada) certified to the standard CAN/CGSB-65.16-2005 (Figure 3.6). Several certified immersion suits were considered for use in these studies. The White's immersion suit was used as it has latex wrist and neck seals that prevent any water from leaking into the suit, as previous studies have shown that water leakage under a suit can increase heat flow compared to being dry (Hall and Polte, 1956; Allan et al., 1985; Light et al., 1987; Tipton and Balmi, 1996). Before the start of each study, the immersion suits were serviced and inspected by the manufacturer, or a certified representative of the manufacturer, to ensure they were in good working order.

Figure 3.6. White's marine abandonment suit.

3.4.1 Undergarments.

Clothing was standardized for the participants in each of the three studies. The clothing ensemble worn by the participants was based on that prescribed by CAN/CGSB-65.16-2005 to be used when testing the thermal protective properties of immersion suits. The ensemble consisted of wool socks, cotton trousers, cotton underwear, cotton undershirt, and a long sleeved cotton shirt (Figure 3.7). For Study 1, participants were provided with socks, trousers, and long sleeved cotton shirt. No cotton undershirt was worn in Study 1, and the participants wore their own underwear. For Studies 2 and 3, the participants were provided with the same clothing as in Study 1, as well as a cotton undershirt and a pair of swimming trunks to replace the cotton underwear. Swimming trunks were provided to the participants so that they could immediately enter a hot tub filled with 40°C to rewarm post-immersion.

Figure 3.7. Typical clothing ensemble, with data loggers, worn by participants underneath the immersion suits.

3.5 Calculations.

3.5.1 Mean Skin Heat Flow (Area Weighted).

Area weighted mean skin heat flow (MSHF) measurements were weighted according to the values reported by Hardy and DuBois (Hardy and DuBois, 1938). The weighting values are listed in Table 3.2.

Table 3.2. Mean skin heat flow and skin temperature measurement weighting values.

Measurement Site	Weighting Value
Right Foot	0.07
Left Shin	0.065
Right Quadricep	0.095
Left Abdominal	0.0875
Right Pectoral	0.0875
Right Underarm	0.07
Forehead	0.07
Right Calf	0.065
Left Hamstring	0.095
Right Lower Back	0.0875
Left Shoulder	0.0875
Left Overarm	0.07

The final MSHF values were divided by 0.95 to take into account the lack of a hand measurement. The equations used to calculated MSHF were:

$\sum$ (Measurement Site · Weighting Value)/0.95 = MSHF

3.5.2 Mean Skin Temperature (Area Weighted).

Area weighted mean skin temperature $\overline{T}_{SK}$ was calculated by the same method as MSHF (3.5.1).

3.5.3 Gastro-intestinal Temperature (T_{GI}).

Change in gastro-intestinal temperature (ΔT_{GI}) was calculated by averaging the measurements during a five minute period at the start of the immersion, and then subtracting the average of a five minute period at the end of the test.

3.5.4 Surface Area.

Surface area (SA) of the participants was calculated by the following formula as described by Gehan and George (Gehan and George, 1970):

$SA\ (m^2) = 0.1644 \cdot WT^{0.51456} \cdot HT^{0.42246}$

Where:

WT = Mass (kg)

HT = Height (m)

3.5.5 $\dot{V}O_2$.

$\dot{V}O_2$ values, as reported by the Cardio Coach, were averaged over a 30 minute period at the end of the immersions for Studies 2 and 3.

3.5.6 Clo Value.

Clo values were calculated based on the following formula as reported by Romet and colleagues (1991):

$clo = (°C \cdot m^2 \cdot W^1) = ([\overline{T}_{SK} - T_W]/MSHF)/0.155$

Where:

$\overline{T}_{SK}$ = Mean skin temperature (°C)

T_W = Water temperature (°C)

MSHF = Mean skin heat flow ($W \cdot m^{-2}$)

3.5.7 Metabolic Heat Production.

Metabolic heat production was calculated using the following formula as described by Peronnet and Massicotte (Peronnet and Massicotte, 1991):

$\dot{M}\ (W \cdot m^{-2}) = (281.65 + 80.65 \cdot \text{RER}) \cdot (\dot{V}O_2 / SA)$

Where:

$\dot{M}$ = Metabolic heat production ($W \cdot m^{-2}$)

RER = Respiratory exchange ratio

$\dot{V}O_2$ = Oxygen consumption ($L \cdot min^{-1}$)

SA = Surface area

RER was given a value of 1.0 since a change of ±0.15 (maximum physiological range for non-protein oxidation) from a reference value of 0.85 would lead to an error of less than 3.6% in $\dot{M}$ (Tikuisis, 1999).

3.5.8 Predicted $\dot{V}O_2$ to Remain in Thermal Balance

Rearranging the equation to calculate clo value in section 3.5.5, MSHF can be predicted ($MSHF_P$) for a given clo value, water temperature, and $\overline{T}_{SK}$.

$MSHF_P = (\overline{T}_{SK} - T_W) / (clo \cdot 0.155)$

Substituting $MSHF_P$ for $\dot{M}$ in the metabolic heat production calculation, as described in section 3.5.6 allows for the calculation of the predicted $\dot{V}O_2$ ($\dot{V}O_{2\,P}$) required to equal the heat lost to the external environment, keeping an individual in thermal balance for a given clo value, water temperature, and $\overline{T}_{SK}$.

$\dot{V}O_{2\,P} = (MSHF_P \cdot SA) / (281.65 + 80.65 \cdot 1).$

3.6 Statistical Analyses.

Sample sizes to have 80% power for each study were determined by power calculations based on a review of results from previously published studies (Steinman et al., 1987; Ducharme and Brooks, 1998). SPSS 18.0 for Windows was used to perform statistical analyses on the data collected from the three studies. The Kolmogorov-Smirnov test was used to determine normality of the data with a P value greater than 0.05 indicative of normally distributed data.

Pearson r correlations were performed using GraphPad InStat with a P value less than 0.05 considered as significant.

When comparing two groups of paired data, paired t tests were performed to detect a significant difference, with a P value of less than 0.05 considered as significant. When comparing three of more groups of paired data, repeated measures analysis of variances (ANOVAs) were performed to detect significant differences, with a P value less than 0.05 considered as significant. If significant differences were detected, Tukey's post hoc tests were performed. Results are presented as means with standard deviation [SD] unless otherwise stated.

Chapter 4 - Study 1: The Effects of Wind and Waves on Skin Heat Flow

4.1 Introduction.

Hypothermia is the primary risk during long-term immersion in cold water (Tipton, 1989; Golden and Tipton, 2002). The length of time it takes a person to develop hypothermia is dependent on several factors such as: temperature of the air and water; body fat percentage (Baker and Daniels, 1956); thermal protection provided by the clothing worn (Steinman et al., 1987); and the weather conditions (Tipton, 1991). Testing of life saving appliances with humans is often performed in calm water pools due to limited access to facilities that are capable of generating repeatable, controlled weather conditions that include wind and waves observed offshore. Current IMO regulations require that immersion suit testing with humans be conducted in calm water pools with a water temperature of 2°C (IMO, 2010). If the suit prevents a drop in deep body temperature of 2°C in six hours, the suit is considered approved for use.

A number of studies have examined the effect of wind and waves on human thermoregulatory responses. While some studies have reported insignificant findings (Hayes et al., 1985; Steinman et al., 1987), others suggest that wind and waves increase the stress placed on the human thermoregulatory system (Tipton, 1991; Ducharme and Brooks, 1998), translating to a faster drop in deep body temperature. Possible limitations in the studies that reported no significant findings were the inability to generate repeatable, realistic offshore conditions across all study volunteers. Study 1 sought to address this knowledge gap by testing a group of participants in conditions representative of that found offshore (both wind and waves) that would be repeatable across the entire study sample size.

Study 1 had two aims. The first was to establish the procedures for testing human participants in the National Research Council of Canada’s Institute for Ocean Technology (NRC-IOT), thereby developing the resources and capabilities of the institute for human testing. NRC-IOT was primarily an engineering institute; the few human studies conducted in the past were done with extensive support from external collaborators. The second goal of Study 1 was to investigate the effect of wind and waves on human skin heat flow.

4.2 Hypotheses.

It was hypothesized that:

H_{01}: There will be no significant differences between mean skin heat flow across all immersion conditions.

H_{A1}: Mean skin heat flow will be significantly greater in Wind + Waves compared to other conditions.

H_{02}: There will be no significant differences in the change in deep body temperature across all immersion conditions.

H_{A2}: Deep body temperature will drop by a significantly greater amount in Wind + Waves compared to other conditions.

4.3 Methods.

Ten males, and two females, volunteered for this experiment. The protocol for this experiment was approved by NRC's REB (#:2007-31). The anthropometrics of the participants is given in Table 4.1.

Table 4.1. Participant anthropometrics for Study 1 (Mean [SD], *n* = 12).

	Age (yrs)	**Height (cm)**	**Mass (kg)**	**Body Fat %**	**Surface Area (m^2)**
Mean [SD]	25.8 [5.9]	176.2 [7.7]	81.7 [13.1]	20.5 [8.9]	2.0 [0.2]
Range	20.0 – 40.0	164.5 – 192.5	66.6 – 116.8	10.4 – 35.7	1.8 – 2.4

Study 1 consisted of four separate data collection sessions, each session separated by at least 24 hours. Participants performed four, one hour immersions in the conditions listed in Table 4.2. Participants started with the Calm condition to allow for a familiarization with the test equipment; subsequent conditions were randomized.

Table 4.2. Study 1 immersion environmental conditions (Mean [SD]).

Condition	**Wind Speed ($m \cdot s^{-1}$)**	**Maximum Wave Height (m)**	**Water Temperature (°C)**	**Air Temperature (°C)**
Calm	0	0	10.87 [0.58]	18.03 [0.36]
Wind	4.24 [0.38][4]	0	10.93 [0.64]	17.97 [0.40]
Waves	0	0.67	10.72 [0.68]	17.61 [0.45]
Wind + Waves	4.24 [0.38]	0.67	11.10 [0.70]	18.14 [0.43]

4.3.1 Procedure.

On the day of each immersion, participants arrived at the facility and changed into the provided test clothing. A research team member applied the heat flow sensors as described in Chapter 3, then the participants donned the immersion suit and proceeded to the test area. The data acquisition equipment was checked for functionality, and then five minutes of baseline data were collected. Once the data were collected, Taigon tubing was looped around the feet of the participant that was connected to a tether system designed to keep them in place once immersed. The participant descended the scaffolding stairs and was manoeuvred into the test position by the research team. Once in the position, the one hour test began.

At the end of the immersion, or when the participant requested for the test to end, they were removed from the water and de-instrumented. After their well-being was assured, the participants were allowed to leave the facility to return for their next scheduled test.

[4] Standard deviation of wind speed at the location of the participant during the wind field calibration.

4.3.2 Thermal Manikin.

A Thermal Instrumented Manikin (TIM) that is used for certifying immersion suits according to CAN/CGSB-65.16-2005 and 65.17-99, and is the same manikin used in the study by Romet and colleagues (1991), was tested alongside the participant. A picture of TIM is presented in Figure 4.1.

Figure 4.1. Thermal instrumented manikin (TIM).

TIM was positioned adjacent to the participants in the water (Figure 4.2) and was positioned in a flotation cradle so that the distance from the water to its mouth, stomach and toes was the same distance as the human participants.

Figure 4.2. TIM and participant in the water during a test.

4.3.3 Data Analysis.

The data analyses procedures described in sections 3.5.1, 3.5.2, 3.5.3, and 3.5.5 were used in Study 1.

Absolute heat flow measurements for each section of TIM were weighted according to the values reported by Romet and colleagues (1991). The individual sections on TIM that reported heat flow values were grouped into three separate segments:

Torso: Abdomen, buttocks, chest, back.
Limbs: Right foot, left foot, right leg, left leg, right arm, left arm, left hand, right hand.
Head: Head.

When comparing to TIM, the measurement sites on the participants were grouped into the same three segments:

Torso: Left abdominal, right pectoral, right lower back, left shoulder.
Limbs: Right foot, left shin, right quadriceps, left hamstring, right underarm, left overarm.
Head: Forehead.

The percent of the total heat flow for each segment, for both the participants and TIM, was calculated as:

Segment heat flow ($W \cdot m^{-2}$) / $\sum$ All segments heat flow ($W \cdot m^{-2}$)

4.3.4 Statistical Analyses.

The statistical analysis procedures described in section 3.6 were used in Study 1.

4.4 Results.

All participants completed all immersion conditions (*n* = 12).

4.4.1 Baseline values.

The baseline values for T_{GI}, $\overline{T}_{SK}$, and MSHF are presented in Tables 4.3 – 4.6

Table 4.3. Study 1 Calm condition baseline values for T_{GI}, $\overline{T}_{SK}$, and MSHF (*n* = 12).

	T_{GI} (°C)	**$\overline{T}_{SK}$ (°C)**	**MSHF ($W \cdot m^{-2}$)**
Mean [SD]	37.31 [0.35]	32.59 [0.63]	44.41 [5.48]
Range	36.62 – 37.93	31.33 – 33.41	35.79 – 57.44

Table 4.4. Study 1Wind condition baseline values for T_{GI}, $\overline{T}_{SK}$, and MSHF (*n* = 12).

	T_{GI} (°C)	$\overline{T}_{SK}$ (°C)	MSHF ($W \cdot m^{-2}$)
Mean [SD]	37.29 [0.39]	32.50 [0.56]	47.96 [4.19]
Range	36.81 – 37.91	31.39 – 33.17	38.14 – 52.07

Table 4.5. Study 1Waves condition baseline values for T_{GI}, $\overline{T}_{SK}$, and MSHF (*n* = 12).

	T_{GI} (°C)	$\overline{T}_{SK}$ (°C)	MSHF ($W \cdot m^{-2}$)
Mean [SD]	37.36 [0.31]	32.71 [0.59]	46.14 [2.93]
Range	36.87 – 37.85	31.39 – 33.17	41.02 – 51.46

Table 4.6. Study 1Wind and Waves condition baseline values for T_{GI}, $\overline{T}_{SK}$, and MSHF (*n* = 12).

	T_{GI} (°C)	$\overline{T}_{SK}$ (°C)	MSHF ($W \cdot m^{-2}$)
Mean [SD]	37.33 [0.25]	32.93 [0.47]	45.81 [4.17]
Range	36.99 – 37.87	31.83 – 33.75	37.37 – 52.52

4.4.2 Mean Skin Heat Flow.

For the participants, MSHF was significantly greater in all conditions compared to Calm (67.21 [4.70]$W \cdot m^{-2}$) (Figure 4.3). MSHF in the Wind + Wave (92.00 [8.39]$W \cdot m^{-2}$) condition was significantly greater than all other immersion conditions. There were no significant differences in MSHF between the Wind (79.60 [6.70]$W \cdot m^{-2}$) and Waves (78.8 [4.52]$W \cdot m^{-2}$) conditions.

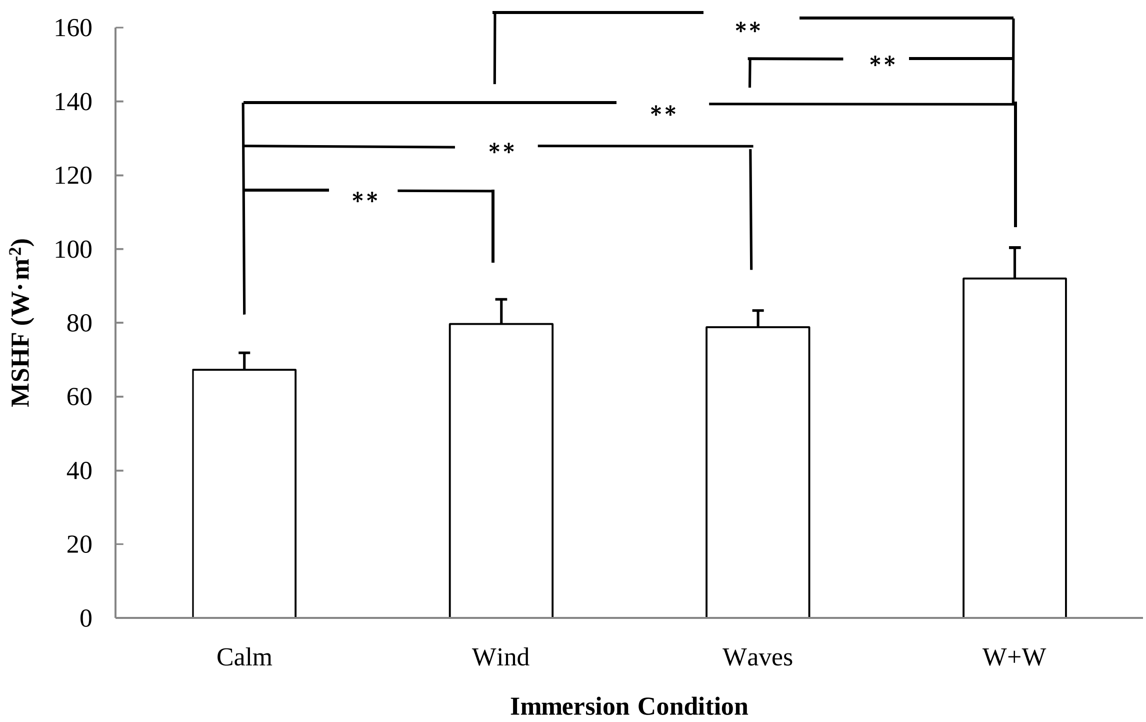

Figure 4.3. Averaged MSHF (W·m^{-2}) of the participants at the end of the one hour immersions (Mean [SD], *n* = 12, ** = P < 0.001).

4.4.3 Mean Skin Temperature Change.

There was a significantly greater decrease in $\overline{T}_{SK}$ during the one hour immersion in the Wind + Wave condition (-3.49 [0.44]°C) compared to Calm (-1.58 [0.62]°C), Wind (-2.49 [0.42]°C), and Waves (-2.62 [0.60]°C) (Figure 4.4). $\overline{T}_{SK}$ decreased by a significantly greater amount in Wind and Waves compared to Calm There was no significant difference in $\overline{T}_{SK}$ decrease between the Wind condition, and the Waves condition.

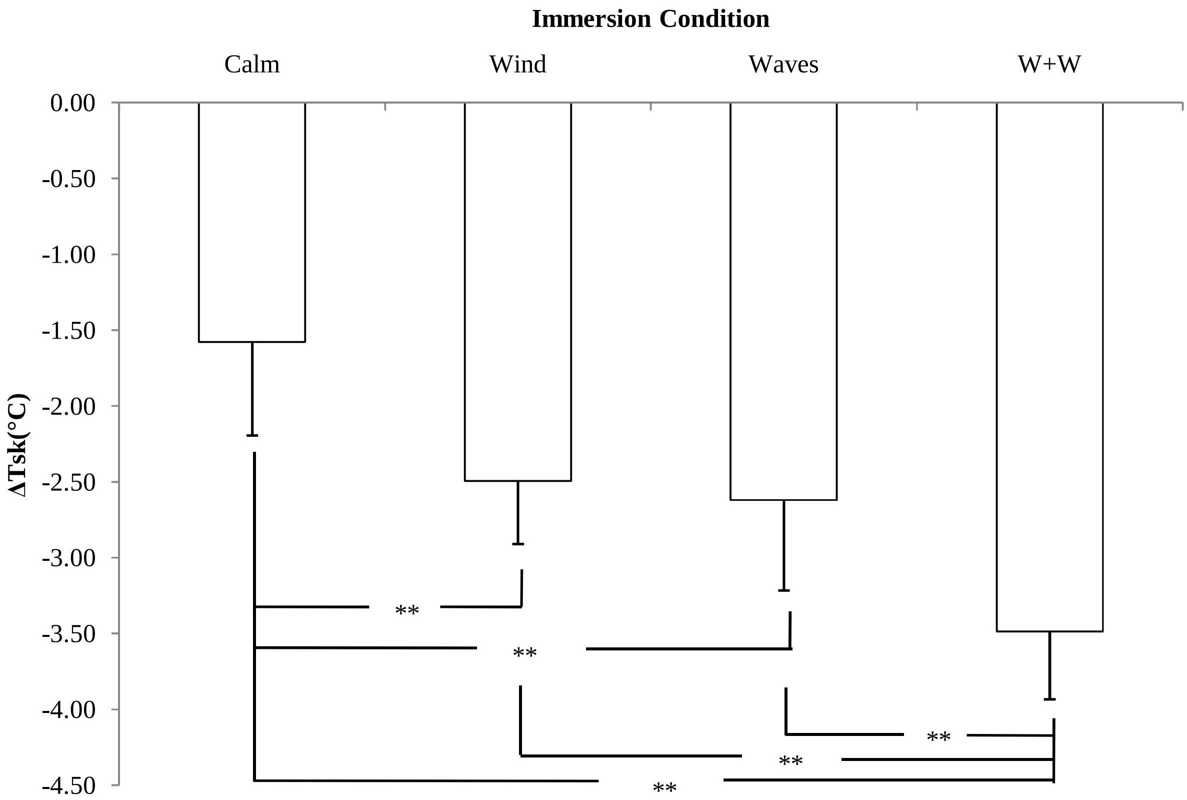

Figure 4.4. Change in $\overline{T}_{SK}$ (°C) during the one hour immersions (Mean [SD], *n* = 12, ** = P < 0.001).

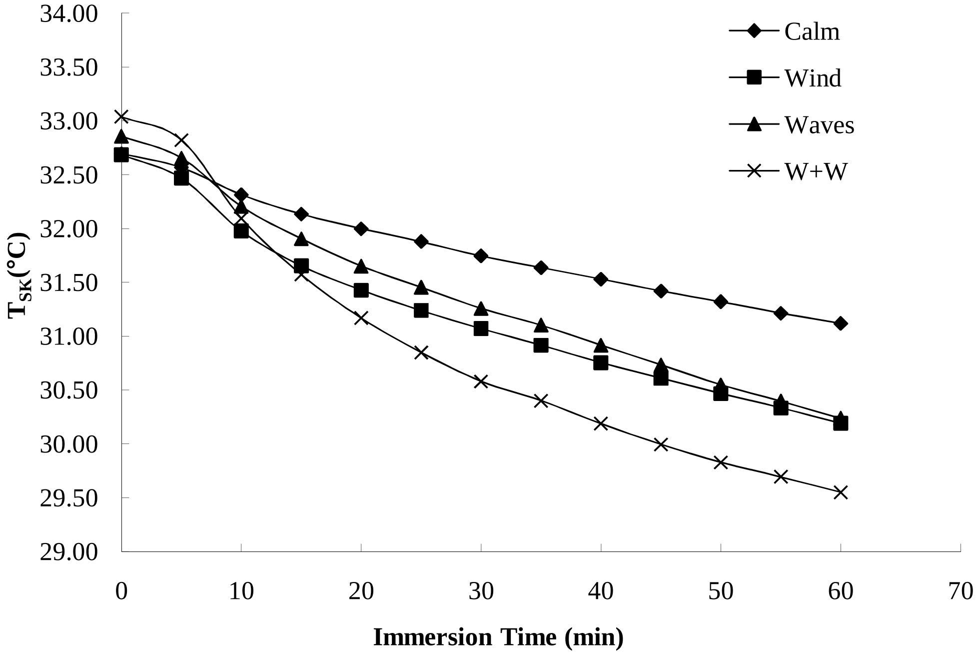

Figure 4.5. Absolute $\overline{T}_{SK}$ (°C) during the one hour immersions (Mean, *n* =12, Average [SD] (°C): Calm: 0.70; Wind: 0.57; Waves: 0.64; W+W: 0.43).

4.4.4 Gastro-Intestinal Temperature Change.

There were no significant differences in the change of T_{GI} during the one hour immersions across all conditions (Figure 4.6). T_{GI} fell –0.13 [0.33]°C in Calm; -0.14 [0.25]°C in Wind; -0.03 [0.29]°C in Waves; and –0.08 [0.27]°C in Wind + Waves.

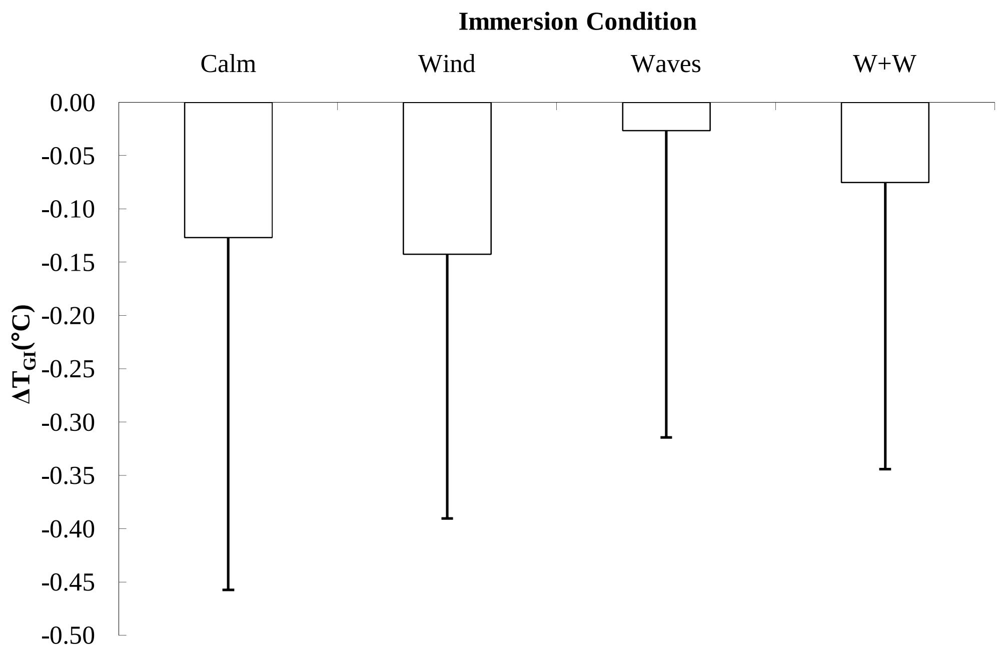

Figure 4.6. Change in T_{GI} (°C) during the one hour immersions (Mean [SD], *n* = 12).

The rate of change in T_{GI} (°C·hr^{-1}) during the last 30 minutes of the immersions is given in Table 4.7.

Table 4.7. Change in T_{GI} (°C·hr^{-1}) during the last 30 minutes of the immersions. (Mean [SD], *n* =12).

	Calm	**Wind**	**Waves**	**W+W**
T_{GI} Change (°C·hr^{-1})	-0.22 [0.28]	-0.26 [0.29]	-0.35 [0.37]	-0.40 [0.25)

There were no significant correlations between body fat percentage and the change in T_{GI} across all immersion conditions (Table 4.8).

Table 4.8. Correlation coefficients (r values) between body fat percentage and change in T_{GI} in Study 1.

	Calm	**Wind**	**Waves**	**Wind + Waves**
Correlation coefficient	-0.10	-0.29	-0.33	-0.19

4.4.5 Clo Values.

The clo values, when measured on the participants, were significantly lower in the Wind + Waves condition (1.4 [0.2]clo) compared to Calm (2.1 [0.4]clo) (Figure 4.7). Clo values for Wind (1.8 [0.3]clo) were significantly lower compared to Calm. There were no significant differences between the clo values for calm and Waves (1.7 [0.2]clo). Clo values reported by TIM were: 1.1 for Calm; 1.0 for Wind; 0.8 for Waves; and 0.8 for Wind + Waves. All these values were lower than those measured with the participants.

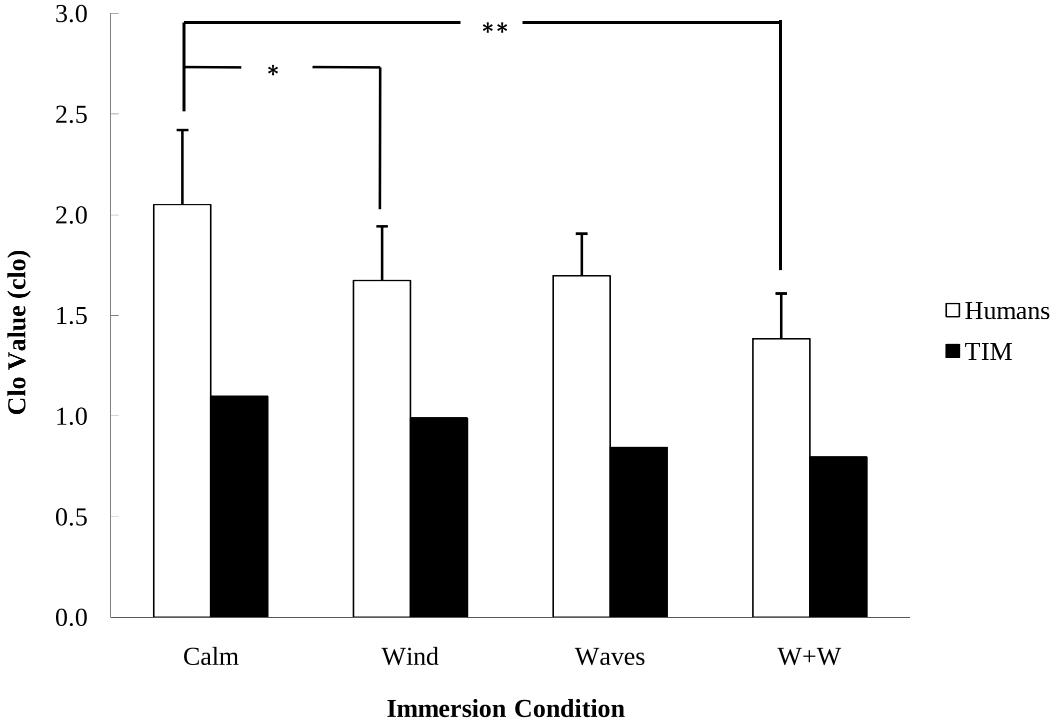

Figure 4.7. Clo values for each immersion condition as measured by the participants and TIM (Mean [SD], *n* = 12, * = P < 0.05, * = P < 0.001).

4.4.6 Participant and TIM Segment Heat Flow.

The weighted heat flow for each segment of the participants and TIM is given in Table 4.9, and presented in Figure 4.8.

Table 4.9. Segment weighted heat flow ($W \cdot m^{-2}$) values for TIM and participants in all immersion conditions (Mean [SD], n = 12).

Condition	Torso		Limbs		Head	
	Participants	**TIM**	**Participants**	**TIM**	**Participants**	**TIM**
Calm	23.69 [3.07]	34.47	35.86 [2.48]	80.55	6.09 [1.12]	9.03
Wind	27.75 [3.34]	36.47	37.15 [3.11]	83.12	12.75 [4.70]	18.39
Waves	27.09 [2.17]	49.17	40.78 [3.01]	91.97	9.03 [2.59]	14.44
W+W	30.29 [4.43]	50.50	40.90 [2.52]	93.06	18.26 [6.57]	28.20

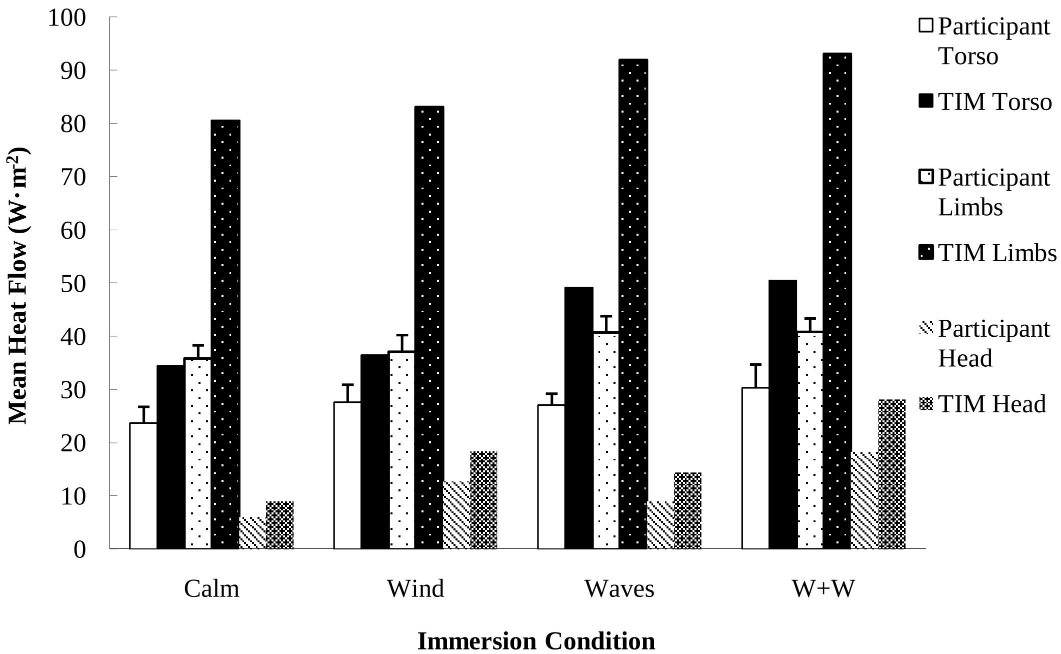

Figure 4.8. Segment weighted heat flow values ($W \cdot m^{-2}$) for TIM and participants in all immersion conditions (Mean [SD], n = 12).

The heat flow difference between the limbs and torso for both the participants and TIM is presented in Figure 4.9.

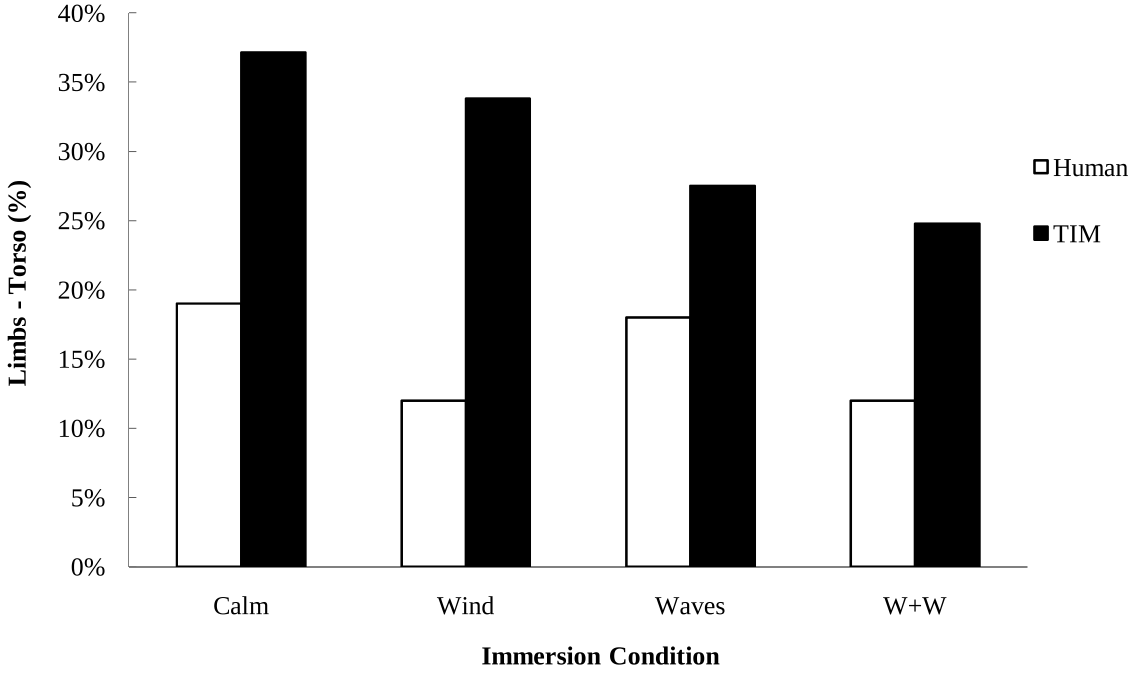

Figure 4.9. Percent heat flow difference between the limbs and torso (% Limbs - % Torso) for participants and TIM (*n* = 12).

In the Calm condition, the participants lost 19% more heat through their limbs compared to the torso; TIM lost 37% more. In the Wind condition participants lost 12% more heat through their limbs compared to the torso; TIM lost 34% more. For Waves, participants lost 18% more heat through the limbs; TIM lost 28% more compared to the torso. For the Wind + Waves condition, the participants lost 12% more through the limbs; TIM, 25%.

4.5 Discussion.

Based on the results, the first null hypothesis is rejected and the alternative is accepted; the Wind + Waves condition did cause a significantly greater increase in MSHF compared to the Calm test condition. The second null hypothesis is accepted, and the alternative is rejected; the Wind + Waves condition did not cause T_{GI} to drop a significantly greater amount compared to other conditions.

The results of Study 1 are in agreement with some previous findings, but in disagreement with others. Similar to the results reported by Ducharme and Brooks (1998), immersions in conditions with waves significantly increased MSHF compared to calm water (Figure 4.3), but this increase did not translate into significant decreases in deep body temperature (Figure 4.6). The lack of significant change in deep body temperature across all conditions is in agreement with the results reported by Hayes and colleagues (1985) and Steinman and colleagues (1987) for immersion dry suits . In the study by Hayes and colleagues, no heat flow values or metabolic rates were reported for the immersions with the clothing ensemble with the largest clo value (0.8 clo). While there was no significant difference reported in that study in the rate of rectal temperature drop, it is not known if there was a significant increase in mean skin heat flow between the calm and waves condition, or whether the study participants increased their metabolic rate to compensate for this increased heat loss.

Compared to the participants, TIM had a much greater heat flow from all segments (Figure 4.8) in each condition. TIM does not possess any thermoregulatory mechanisms such as vasoconstriction; instead it maintains a set temperature point for the surface of each segment (32°C for this study). The participants did not maintain a set skin temperature point throughout the immersions; instead they cooled throughout the tests and had a lower $\overline{T}_{SK}$ at the end compared to the beginning (Figure 4.5). With a lower $\overline{T}_{SK}$, the thermal gradient between the skin and the water would have been reduced, resulting in lower heat flow compared to that which was measured with TIM who maintained a “skin temperature” of 32°C. These findings agree with the some of the earlier work by Romet and colleagues (1991) who found that TIM had greater heat flow in the abdomen, calf, and arm compared to humans. In the previous work by Romet and colleagues (1991), humans had slightly greater heat flow, from the back of the torso, in high insulation suits (clo > 0.35), and low insulation suits (clo < 0.20). In medium insulation suits (clo 0.2 - 0.35), manikins had higher heat flow from the back of the torso (Romet et al., 1991).

Earlier work by Tipton and Balmi (1996) found that leakage over the limbs of a thermal manikin result in a greater reduction in measured suit insulation than an equivalent leak over the torso, and the opposite to be true for humans. Tipton and Balmi also suggest that when measuring immersion suit insulation on a thermal manikin, overall insulation values can be improved by adding more insulation to the limbs compared to the torso (Tipton and Balmi, 1996). They also have shown that 500mL of water applied over the limbs of participants produced a rate of fall of T_{re} equivalent to that seen with no water leakage underneath the immersion suit. Some of the findings from the current study agree with the results seen by this earlier work such as how more heat was lost from the limbs of TIM compared to its torso (Figure 4.9) across all immersion conditions. However, the participants also lost more heat from their limbs compared to the torso (Figure 4.9), which is in disagreement with the findings of Tipton and Balmi where the participants lost less heat through the limbs compared to the torso. This discrepancy is probably due to: longer immersion times in the Tipton and Balmi study, allowing heat loss to settle, and uninsulated suits, both causing maximum vasoconstriction leaving heat loss from the torso as the major route of heat loss. In the present study, TIM lost 37% more heat through its limbs than the torso, while the humans lost only 19% more in the Calm condition (Figure 4.9). As wind and waves are added to the immersion conditions, the difference between limb and torso heat flow on TIM is reduced, with the manikin losing only 25% in the Wind + Wave condition, while the humans lost only 12% more through the limbs (Figure 4.9).

For the majority of the conditions in the current study, the $\overline{T}_{SK}$ of the participants remained above 30°C (Figure 4.5); the temperature associated with maximum vasoconstriction (Barcroft and Edholm, 1945), which would have resulted in an increase in internal insulation as muscle and tissue become unperfused. Given the $\overline{T}_{SK}$ values measured in the current study, it is unlikely that the participants were maximally vasoconstricted; resulting in a higher amount of heat loss through the limbs than would be the case with maximum vasoconstriction, and higher than that seen from the torso. If the thermal stress on the participants had increased, a stronger thermoregulatory response (i.e. more intense vasoconstriction) would have been required in order to ensure this stress remained compensable. It is probable that more intense vasoconstriction would have resulted in reduced heat loss from the limbs, and more heat being lost through the torso compared to the limbs, as seen by Tipton & Balmi (1996).

In the current study, since TIM lost more heat through the limbs compared to its torso, it would be more beneficial for extra insulation to be added to the limbs compared to the torso; the opposite of what would be beneficial to humans as reported by previous work (Tipton and Balmi, 1996). This should be considered when designing immersion suits: extra insulation over the limbs may help a suit pass a thermal certification test using a manikin (such as in CAN/CGSB-

65.16-2005), but would provide little benefit to humans, who will ultimately use the suit, if more heat is being lost from the torso, compared to the limbs, due to vasoconstriction.

In the study by Steinman and colleagues, the rate of rectal temperature cooling was significantly higher in calm water compared to the rough condition for one of the immersion suits tested (Suit A) (Steinman et al., 1987). The authors reported that in the rough water condition, the rectal temperature of many of their participants actually increased over the first 30 minutes, and then followed a near linear decrease (Steinman et al., 1987). It is unlikely that the initial rise in deep body temperature reported was due to a combination of vasoconstriction and increased shivering, similar to the trend seen in the traditional hypothermia curve, given the temperature of the water (10-11°C) and the insulation and protection of the immersion suits were worn. When the participants wore immersion suit A, their $\overline{T}_{SK}$ fell ~3°C in calm conditions and ~2°C in the rough conditions, while in suit B it fell ~2°C in both conditions. Assuming that the participants in the study by Steinman and colleagues started with a $\overline{T}_{SK}$ of 33°C (resting values), the drops in $\overline{T}_{SK}$ reported would still put the absolute values above those associated with maximum vasoconstriction (30°C) (Barcroft and Edholm, 1943). It is possible that this initial rise in rectal temperature reported by Steinman and colleagues is due to the increased physical effort (and consequently increasing metabolic rate) by the participants to maintain airway freeboard in the rough water condition as described by the authors (Steinman et al., 1987). Steinman and colleagues report that the higher heart rate measured in the rough water condition, compared to calm water, indicate increased metabolic heat production. With no need to physically exert themselves in the Calm condition, deep body temperature may not have risen initially, leading to the significantly greater rate of cooling observed in this condition. For immersion suit B, there was no significant difference in the rate of rectal temperature decline, which is in agreement with the results of the current study. It was reported that neither immersion suit ensemble leaked, so the increased cooling in calm water is likely to have been the result of the increased metabolic heat production via physical exertion in the rough water condition in the study by Steinman and colleagues.

The lack of significant differences in the water and air temperatures across conditions in Study 1, coupled with the significantly greater increase in MSHF for the conditions with wind and waves, resulted in decreasing clo values as conditions became more turbulent. This reduction in clo value, when moving from Calm, was observed in the participants and TIM (Figure 4.7). The reduction was greater in the participants compared to TIM, with the Wind + Waves condition giving the greatest drop in clo value of 33% (Figure 4.7). These findings are in agreement with those reported by Romet and colleagues (1991); they found that the manikin always reported a lower clo value than the participants in turbulent conditions. They also state that while there are obvious differences between humans and manikins, use of the manikin data will err on the side of caution and over-estimate heat loss compared to the former (Romet et al., 1991).

Since there was no significant difference in the rate of decline of T_{GI} in the Study 1 participants across immersion conditions, they were able to successfully defend against this decrease in thermal insulation (increase in heat flow) and maintain a stable deep body temperature. Change in T_{GI} did not significantly correlate to body fat percentage in this study, as it has in previous work (Hayward and Eckerson, 1984). If the participants in the current study had not been able to compensate for the increased thermal strain caused by wind and waves, and had a reduction in T_{GI}, we would have expected slower rates of cooling in those with a higher body fat percentage. The lack of negative correlation suggests that the participants with a lower body fat percentage experienced a similar rate of change of T_{GI} as those with a higher body fat percentage. It is not known if the participants increased their heat production via shivering since metabolic rate was not measured in Study 1. Additionally, the short immersion duration of one hour, high level of thermal insulation provided by the immersion suits, and water and air temperatures may not have challenged the thermoregulatory system of the participants. It is possible that the participants thermoregulated by decreasing skin blood flow a little (increasing vasoconstriction and consequently increasing body insulation). This would be reflected in a lower skin temperature (Figure 4.4) and implies that they were not maximally vasoconstricted in the less stressful conditions.

4.5.1. Implications for Future Studies.

The initial pilot work described in Study 1 was successful in establishing the resources and techniques needed for more in-depth future studies in a safe and reproducible manner, as well as providing valuable experience to the research team and the staff at NRC-IOT. The results from

Study 1 show that an environment consisting of *both* wind and waves will cause the greatest increase in skin heat flow compared to the other conditions. The lack of metabolic measurements in Study 1 prevented any conclusions from being drawn on how much additional strain an environment with wind and waves would place the human thermoregulatory system under, other than it will cause a significant increase in skin heat flow compared to calm water. With the short immersion duration in Study 1, it is not unexpected that there was no significant drop in T_{GI} as even lightly clothed humans can take up to 30 minutes to develop hypothermia in ice water (Hayward and Eckerson, 1984).

For hypothermia to occur during immersion in cold water, heat lost from the body to the external environment must exceed that generated via metabolism (Tikuisis, 1999). That is, the thermal stress must be uncompensable by the thermoregulatory system. Even though metabolic rate was not measured in Study 1, the heat lost to the environment during the Wind + Waves condition, as measured by heat flux transducers ($92.00 \pm 8.39 W \cdot m^{-2}$), was well below the reported maximum metabolic heat production of approximately $208.35 W \cdot m^{-2}$ measured in a study by Tipton in which participants were unable to maintain a stable deep body temperature in 4°C, turbulent water while wearing immersion suits (Tipton, 1991). Additionally, for the majority of the immersion conditions, the $\overline{T}_{SK}$ of the participants did not fall below 30°C and therefore it is likely that they were not maximally vasoconstrcited. More intense vasoconstriction would have resulted in less skin heat flow, reducing the rate of heat loss from the body. This would suggest that the participants were well within their ability to thermoregulate, but it was not known how much extra demand (i.e. increase in $\dot{V}O_2$ and increased vasoconstriction) it took for them to compensate for this increase in heat flow.

The heat flow reported by TIM agreed with the previous work by Tipton and Balmi (1996) in that the manikin in the present study lost a greater amount of heat from the limbs (65% of total heat flow) than the torso (28%). Based on these results this would suggest that the optimal design for an immersion suit would concentrate approximately 65% of the total suit insulation over the limbs, and 28% over the torso since the majority of the heat was lost through the limbs. The participants in the present study lost more heat through the limbs (55% of total heat flow) compared to the torso (36%). These results from the participants would suggest a configuration with 55% of the insulation over the limbs and 36% over the torso in order to reduce the maximum amount of heat flow to the water. However, these human results are in disagreement with the findings reported by Tipton and Balmi (1996) in which those participants had 61% of the total heat flow from their torsos, and only 39% was from their limbs, suggesting that the optimal insulation configuration would have more over the torso compared to the limbs. For reasons mentioned previously, the conditions in the study by Tipton and Balmi (colder water temperatures, longer immersion times, lower clo value of immersion suit) caused a greater amount of strain on the thermoregulatory system of their participants resulting in a stronger response *i.e.* more intense vasoconstriction. This resulted in reduced blood flow to their extremities, lessening the amount of heat lost from them compared to the torso. The conditions in the present study were not strong enough to evoke a similar thermoregulatory response from the participants, resulting in more heat flow from the limbs compared to the torso.

These contradicting results from the two studies demonstrate the change the thermoregulatory system can have on human thermal responses, and why it is important to test in conditions representative of those found offshore. In less stressful conditions (*i.e.* the current study), humans will lose more heat through the limbs compared to the torso; a trend similar to thermal manikins. In more stressful conditions, such as those found in the study by Tipton and Balmi (1996), humans will lose more heat from the torso compared to the limbs due to stronger thermoregulatory responses; the opposite of what occurs in thermal manikins. This has important implications with regards to how immersion suits are designed, and if they will be skewed towards benefitting the certifying thermal manikin more than the humans who will ultimately use them. Future studies should attempt to address this difference between humans and manikins, and possibly develop correction factors between the two.

It is concluded that immersions in wind and waves will significantly increase MSHF compared to calm water conditions. However, this increase in MSHF may not directly translate to a drop in deep body temperature if it can be compensated for by the human thermoregulatory system (i.e. shivering and vasoconstriction) and the humans remain in the “thermoregulatory” zone.

Chapter 5 - Study 2: Effects of Varying Wind and Wave Conditions During 3 Hour Immersions on Human Thermoregulatory Responses

5.1 Introduction.

In the previous pilot study (Study 1 – Chapter 4), it was found that wind and waves together produced the greatest increase in MSHF in the immersed participants. The Wind condition, and Waves condition produced significantly greater increases in MSHF compared to Calm, but significantly less than the Wind + Waves condition. The significant increase in MSHF did not result in significantly greater falls in deep body temperature of the participants. This lack of difference could have been due to: the relatively temperate water and air conditions; the high clo value of the immersion suit worn; and the short immersion duration. Even in near 0°C water, hypothermia can take 30 minutes or longer to develop in unprotected humans (Hayward and Eckerson, 1984). With the high level of insulation provided by the immersion suit in the water temperatures tested, immersion durations would have to be extended past an hour for any effect of increased MSHF on deep body temperature to be measured. With the exception of the Ducharme and Brooks study (Ducharme and Brooks, 1998), the majority of immersion studies in the past have had durations of longer than an hour. Hayes and colleagues (1984) had immersion durations of four hours for specific clothing ensembles; Steinman and colleagues in 1987 had immersion durations of 90 minutes; and Tipton in 1991 had participants perform four hour immersions (Hayes et al., 1985; Steinman et al., 1987; Tipton, 1991; Tipton and Balmi, 1996). Similar to the results seen in Study 1, Ducharme and Brooks reported no significant changes in deep body temperature in their participants during the hour long immersions (Ducharme and Brooks, 1998).

Previous immersion studies have often only compared immersions in calm water to a single weather condition, consisting of a specific wave height and wind speed (Hayes et al., 1985; Tipton, 1991), or in conditions where there was variation in the environment across participants (Steinman et al., 1987). The results from Study 1 show that an environment of wind and waves together may cause the greatest increase in MSHF, but it was unknown how *varying* weather conditions would affect it. Building upon the findings of Study 1, the objective of Study 2 was to measure the effect that two separate weather conditions had on immersed participants, to determine if heat flow would increase in a linear fashion in relation to increasing wind and waves.

5.2 Hypotheses.

It was hypothesized that:

H_{O1}: Compared to Calm, immersions in conditions with faster wind speeds and higher wave heights will not significantly increase the amount of MSHF compared to less turbulent conditions.

H_{A1}: Compared to Calm, immersions in conditions with faster wind speeds and higher wave heights will significantly increase the amount of MSHF compared to less turbulent conditions.

H_{O2}: Compared to Calm, immersions in conditions with faster wind speeds and higher wave heights will not result in a significantly greater decrease in deep body temperature compared to less turbulent conditions.

H_{A2}: Compared to Calm, immersions in conditions with faster wind speeds and higher wave heights will result in a significantly greater decrease in deep body temperature compared to less turbulent conditions.

5.3 Methods.

Twelve healthy male participants volunteered for this study and gave their written consent before participating. With the exception of one individual, the participants were different from those who volunteered for Study 1. The current study was approved by NRC's REB (#:2008-68). The physical characteristics of the participants are given in Table 5.1.

Table 5.1. Physical characteristics of the participants in Study 2 (Mean [SD], *n* = 12).

	Age (yrs)	**Height (cm)**	**Mass (kg)**	**Body Fat %**	**Surface Area (m^2)**
Mean [SD]	23.9 [3.3]	181.0 [4.9]	83.2 [4.9]	16.8 [4.1]	2.0 [0.1]
Range	21.0 – 31.0	174.0 – 192.0	67.9 – 99.0	10.3 – 24.4	1.8 – 2.3

Study 2 consisted of three separate data collection sessions, separated by at least 48 hours. In addition to the Study 1 clothing, participants also wore a cotton undershirt, swim trunks, and an external bladder for urine collection. The external bladder consisted of a condom catheter connected to a Travel John disposable urinal (Reach Global Industries, Irvine, CA, USA), sealed with duct tape. All clothing was provided to the participants by the research team in order to standardize clothing ensembles. Participants performed three separate, three hour immersions in the conditions listed in Table 5.2.

Table 5.2. Immersion conditions for Study 2.

Condition	**Max Wave Height (m)**	**Mean Wind Speed ($m \cdot s^{-1}$)**	**Mean Water Temperature [SD] (°C)**	**Mean Air Temperature [SD] (°C)**
Calm	0	0	11.14 [0.24]	17.17 [0.51]
Weather 1	0.34	3.5	10.93 [0.41]	17.36 [0.40]
Weather 2	0.67	4.6	10.85 [0.32)]	17.34 [0.42]

5.3.1 Procedure.

The order of immersions for the participants were randomly allocated to a Latin Square design. The procedure used in Study 1 to get the participants ready for the immersion was used again in Study 2. Prior to collecting the baseline data, the participants inserted noise reducing headphones that were connected to a portable FM radio. After the baseline data were collected, the participants looped their feet through Taigon tubing and entered the water. Once in position, the three hour test began. Participants were able to watch movies during the immersion on a screen constructed above the wind machines, with the audio being broadcast by an FM transmitter, picked up by their radio.

At the end of the immersion, or when the participant requested for the test to end, they were removed from the water and de-instrumented. Participants were then rewarmed in a circulating water bath filled with 40°C water. Once the deep body temperature of the participant approached pre-immersion values, they were removed from the water and provided with hot beverages and snacks. After their well-being was assured, the participants were allowed to leave the facility to return for their next scheduled test.

5.3.2 Data Analyses.

The data analysis procedures described in sections 3.5.1 – 3.5.5 were used in Study 2.

5.3.3 Statistical Analyses.

The statistical analyses described in section 3.6 were used in Study 2.

5.4 Results.

All participants completed all immersion conditions (*n* = 12).

5.4.1 Baseline Values.

The baseline values for T_{GI}, $\overline{T}_{SK}$, MSHF, and $\dot{V}O_2$ are presented in Tables 5.3 - 5.5

Table 5.3. Study 2 Calm condition baseline values for T_{GI}, $\overline{T}_{SK}$, MSHF, and $\dot{V}O_2$ (n = 12).

	T_{GI} (°C)	$\overline{T}_{SK}$ (°C)	MSHF (W·m^{-2})	$\dot{V}O_2$ (L·min^{-1})
Mean [SD]	37.31 [0.48]	32.31 [0.80]	47.78 [4.41]	0.323 [0.069]
Range	36.57 – 38.48	30.13 – 33.08	42.00 – 55.21	0.264 - 0.510

Table 5.4. Study 2 Weather 1 condition baseline values for T_{GI}, $\overline{T}_{SK}$, MSHF, and $\dot{V}O_2$ (n = 12).

	T_{GI} (°C)	$\overline{T}_{SK}$ (°C)	MSHF (W·m^{-2})	$\dot{V}O_2$ (L·min^{-1})
Mean [SD]	37.28 [0.34]	32.47 [0.34]	47.46 [4.10]	0.316 [0.054]
Range	36.66 – 37.81	31.97 – 32.89	41.47 – 54.71	0.225 - 0.414

Table 5.5. Study 2 Weather 2 condition baseline values for T_{GI}, $\overline{T}_{SK}$, MSHF, and $\dot{V}O_2$ (n = 12).

	T_{GI} (°C)	$\overline{T}_{SK}$ (°C)	MSHF (W·m^{-2})	$\dot{V}O_2$ (L·min^{-1})
Mean [SD]	37.27 [0.27]	32.67 [0.53]	47.51 [5.42]	0.338 [0.074]
Range	36.67 – 37.77	31.99 – 33.65	37.41 – 55.55	0.240 - 0.465

5.4.2 Mean Skin Heat Flow.

Compared to Calm (62.96 [2.98]W·m^{-2}), MSHF was significantly greater in Weather 1 (76.75 [6.26]W·m^{-2}) and in Weather 2 (79.53 [6.24]W·m^{-2}) (Figure 5.1). There were no significant differences in MSHF between the two weather conditions.

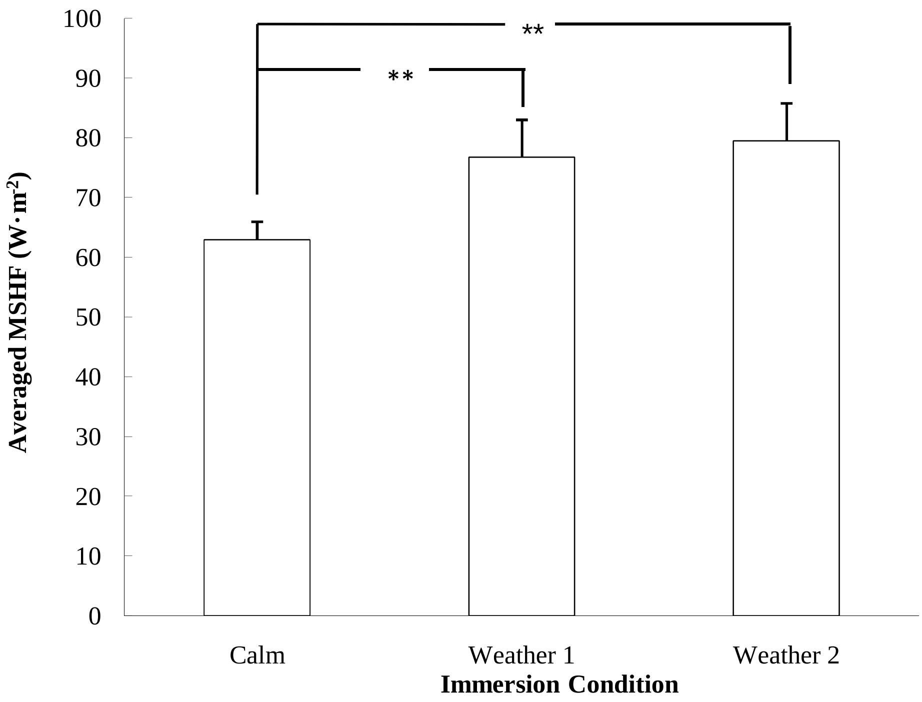

Figure 5.1. Averaged MSHF (W·m^{-2}) at the end of the three hour immersions (Mean [SD], *n* = 12, ** = P < 0.001).

5.4.3 Mean Skin Temperature Change.

Immersions in the Weather 2 condition produced a significantly greater decrease in $\overline{T}_{SK}$ (-5.09 [0.79]°C) compared to Calm (-3.39 [0.39]°C) (Figure 5.2). The drop of $\overline{T}_{SK}$ in the Weather 1 (-4.36 [0.74]°C) was significantly different compared to the values measured in Calm (Figure 5.2). There was a significant difference in the drop of $\overline{T}_{SK}$ between Weather 1 and Weather 2.

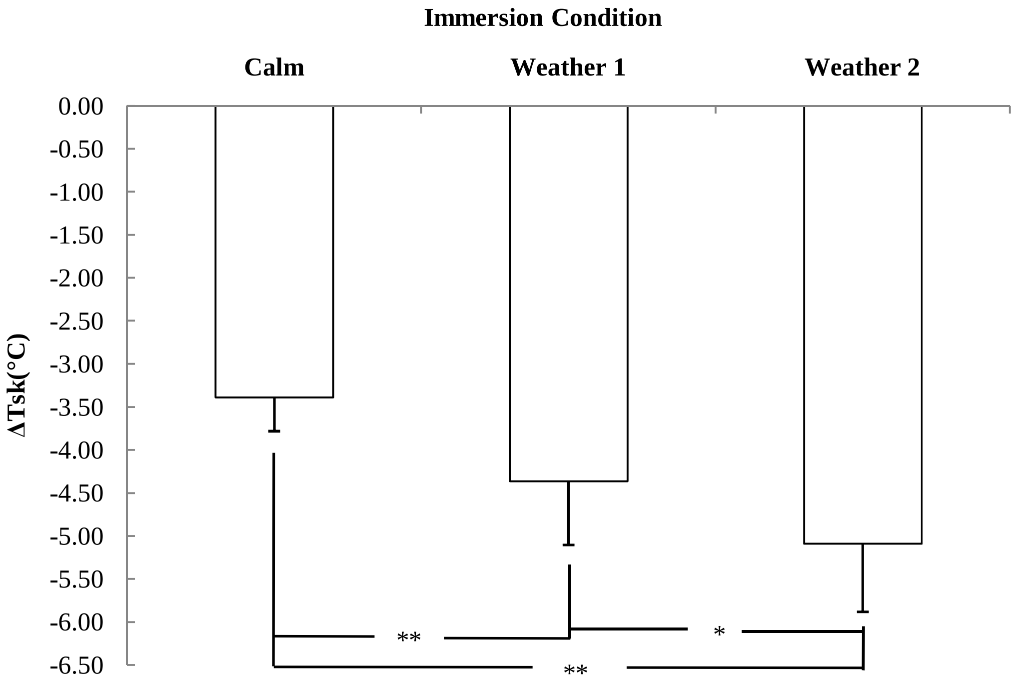

Figure 5.2. Change in $\overline{T}_{SK}$ (°C) during the three hour immersions. (Mean [SD], *n* = 12, * = P < 0.05, ** = P = 0.001.)

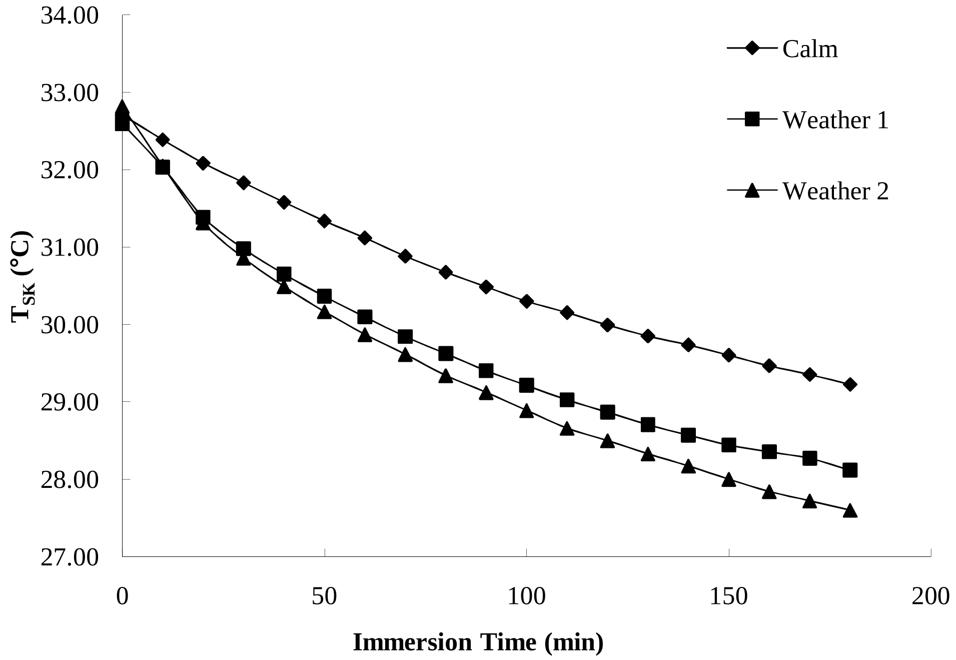

Figure 5.3. Absolute $\overline{T}_{SK}$ (°C) during the three hour immersions (*n* = 12, Average [SD] (°C) Calm: 0.62, W1: 0.48, W2: 0.61).

5.4.4 Gastro-Intestinal Temperature Change.

There were no significant differences in the change in T_{GI} across all conditions during the immersions. T_{GI} change in Calm was –0.10 [0.31]°C; -0.29 [0.30]°C in Weather 1; and –0.20 [0.28]°C in Weather 2 (Figure 5.4).

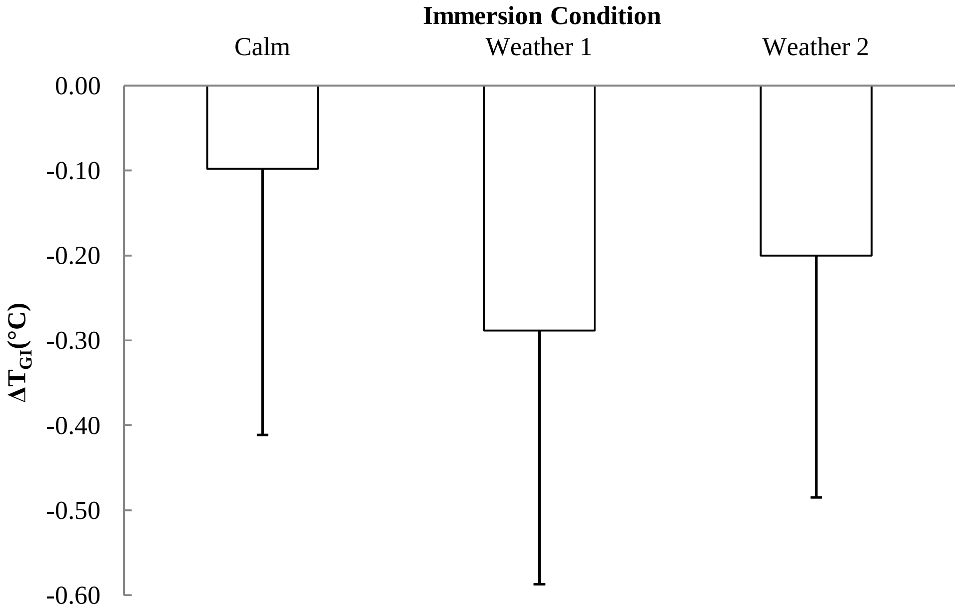

Figure 5.4. Change in T_{GI} (°C) during the three hour immersions. (Mean [SD], *n* = 12.)

The rate of change of T_{GI} (°C·hr^{-1}) during the last 30 minutes of the immersions is given in Table 5.6

Table 5.6. Rate of change in T_{GI} (°C·hr^{-1}) during the last 30 minutes of the immersions (Mean [SD], *n* = 12).

	Calm	**Weather 1**	**Weather 2**
T_{GI} Change (°C·hr^{-1})	-0.01 [0.32]	0.01 [0.19]	-0.17 [0.36]

There were no significant correlations between body fat percentage and change in T_{GI} (Table 5.7).

Table 5.7. Correlation coefficients (r values) between body fat percentage and change in T_{GI} in Study 2.

	Calm	**Weather 1**	**Weather 2**
Correlation coefficient	0.23	0.29	0.17

5.4.5 $\dot{V}O_2$ During the Last 30 Minutes of Immersion.

There were no significant differences in the measured $\dot{V}O_2$ values during the last 30 minutes of immersion across all immersion conditions. Mean $\dot{V}O_2$ during the last 30 minutes of immersion in Calm was 0.325 [0.054]$L \cdot min^{-1}$; in Weather 1 it was 0.332 [0.108]$L \cdot min^{-1}$; and in Weather 2 it was 0.365 [0.080]$L \cdot min^{-1}$ (Figure 5.5).

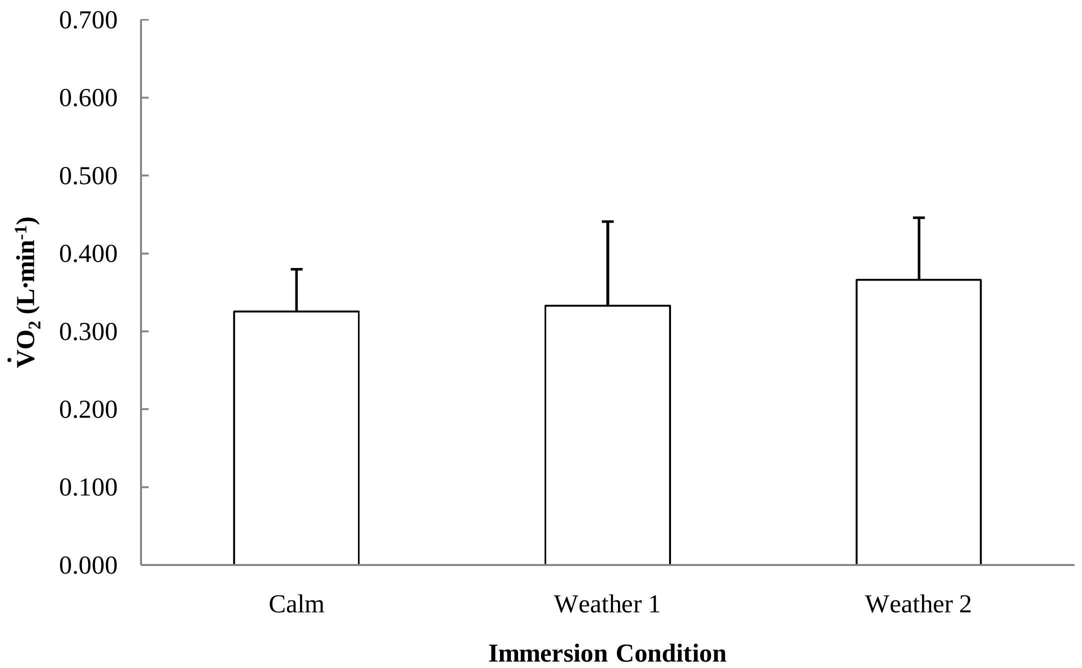

Figure 5.5. $\dot{V}O_2$ ($L \cdot min^{-1}$) during the last 30 minutes of immersion (Mean [SD], *n* = 12.).

5.4.6 Clo value.

Clo values were significantly lower in both Weather conditions compared to Calm (Figure 5.6). The mean clo value in Calm was 1.9 [0.1]; 1.5 [0.1] in Weather 1; and 1.4 [0.1] in Weather 2. There were no significant differences in clo values between the two Weather conditions.

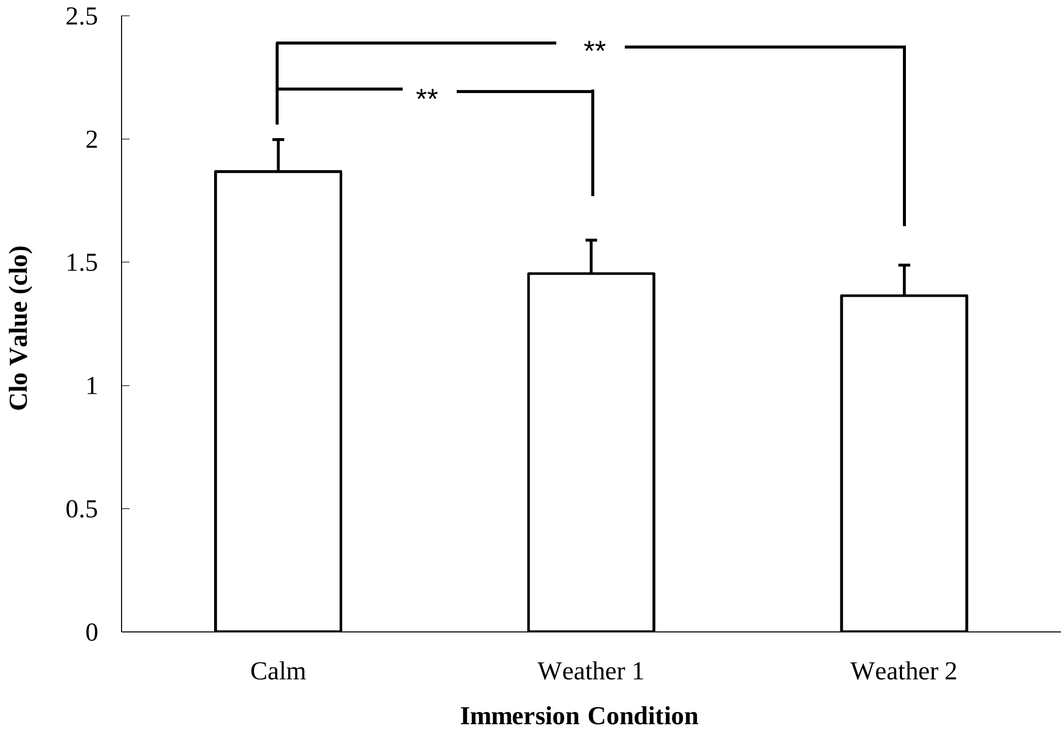

Figure 5.6. Clo value at the end of the three hour immersions. (Mean [SD], *n* = 12, ** = P < 0.001).

5.5 Discussion.

The results from this experiment confirm those of the previous study (Study 1). Immersions in conditions with wind and waves produced a significantly greater increase in MSHF compared to calm water. In Study 1, MSHF was 67.21 [4.70]$W \cdot m^{-2}$ at the end of the one hour immersion, and in the current study it was 62.96 [2.98]$W \cdot m^{-2}$. In the current study, the MSHF for both Weather conditions (Weather 1: 76.75 [6.26]$W \cdot m^{-2}$; Weather 2: 79.53 [6.24]$W \cdot m^{-2}$) was lower than that measured during the Wind + Waves condition in Study 1 (92.00[8.39]$W \cdot m^{-2}$). For Study 1, MSHF was measured at the end of a one hour immersion, and in the present study it was measured at the end of a three hour immersion. The participants in the present study had a numerically greater drop in $\overline{T}_{SK}$ compared to those in Study 1 due to the longer immersion times. A lower $\overline{T}_{SK}$ in the present study, will have resulted in a smaller thermal gradient between the skin and the water; this will result in a lower MSHF.

The first null hypothesis is rejected: compared to Calm, immersions in conditions with faster wind speeds and higher wave heights did significantly increase mean skin heat flow compared to less turbulent conditions. The second null hypothesis is accepted: compared to Calm, immersions in conditions with faster wind speeds and higher wave heights did not result in a significantly greater drop in T_{GI} compared to less turbulent conditions.

Similar to Study 1, there were no significant differences in the change in the T_{GI} of the participants in the present study. Even with the increased immersion duration of three hours, little change was measured in T_{GI} across all immersion conditions, and despite the increased MSHF due to the addition of wind and waves. Also similar to Study 1, there were no significant correlations between body fat percentage and change in T_{GI}.

The measured $\dot{V}O_2$ for the participants demonstrate that the immersion conditions in the present study did not overwhelm the thermoregulatory system. Peak shivering intensity of humans has been reported at a $\dot{V}O_2$ of 1.57$L \cdot min^{-1}$ (Eyolfson et al., 2001), however the conditions in that study were designed to illicit the greatest shivering response possible. The value of 1.14$L \cdot min^{-1}$ reported by Tipton (1991) for participants unable to stabilize falling deep body temperature is more applicable to the current study and conditions. The participants in the current study had a mean $\dot{V}O_2$ of 0.365 [0.080]$L \cdot min^{-1}$ in Weather 2 (Figure 5.5); much less than 1.14$L \cdot min^{-1}$ which suggests that they were still well within their ability to generate extra heat through shivering. With no significant difference in $\dot{V}O_2$ values between immersion conditions, and a significantly greater drop in $\overline{T}_{SK}$ between Calm and Weather 2, it is likely that the participants vasoconstricted to compensate for the significantly greater increase heat flow due to wind and waves without increasing the intensity of their shivering significantly. The $\overline{T}_{SK}$ of the participants did drop below 30°C in all three conditions (Figure 5.3), the temperature at which maximum vasoconstriction has been reported to occur (Barcroft and Edholm, 1945). In the current conditions tested, this degree of vasoconstriction appears to have been sufficient for the participants to compensate for the increased MSHF and maintain a stable deep body temperature. The reduction in blood flow to the extremities will have resulted in less heat loss, and increased tissue insulation. The increased heat loss was compensated for by the thermoregulatory system, with little additional strain, resulting in no change in T_{GI}. With immersion $\dot{V}O_2$ values (Figure 5.5) not significantly greater compared to baseline measurements (Tables 5.3 – 5.5), the conditions the participants were tested in did not exert enough thermal stress for them to compensate with significant increases in metabolic heat production.

The results of the present study are in agreement with those reported by Ducharme and Brooks (1998). Immersions in conditions with wind and waves produced a significantly greater amount of MSHF compared to calm conditions. In the present study, MSHF was not significantly different between Weather 1 and Weather 2, even though the latter condition had higher waves and faster wind speeds. Ducharme and Brooks reported a similar finding, in that there was little difference measured in MSHF for their participants in wave heights ranging from 30 to 50cm (Ducharme and Brooks, 1998). The findings of Witherspoon and colleagues show that heat flow due to convection will increase as fluid velocity increases, but will reach a maximum value, at which point further increases in velocity will result in negligible increases in heat flow (Figure 2.1) (Witherspoon et al., 1971). Small increases in water velocity can disrupt the boundary layer around the participant, resulting in significant increases in heat flow (Witherspoon et al., 1971). The water particle velocity in the Weather 1 condition was at a sufficient speed to produce the maximum amount of heat flow due to convection. The implication of this is that immersions in even “mild” conditions, such as Weather 1 in the present study (Wind speed: $3.5 m \cdot s^{-1}$; Max wave height: 0.34m), is enough to significantly increase MSHF (Figure 5.1) and significantly reduce the clo value of an immersion suit (Figure 5.6). It might be assumed that it would take immersions in rough seas (breaking waves, wind driven spray, etc.) to significantly reduce expected survival time due to increased heat loss, but immersions in perceptually mild conditions may also significantly reduce survival times compared to calm water.

Similar to the findings reported by Hayes and colleagues (Hayes et al., 1985) and Steinmein and colleagues (Steinman et al., 1987), the participants in the current experiment did not experience a significant drop in deep body temperature. Hayes and colleagues reported similar findings in their experiment. Even though energy expenditure was increased in waves, the result in that experiment was not statistically significant (Hayes et al., 1985). Change in $\overline{T}_{SK}$ did not differ significantly between the calm and wave conditions in the study by Steinman and colleagues (Steinman et al., 1987). The falls in $\overline{T}_{SK}$ for both immersion suits worn were greater than those observed in the current study. For immersion suit A in their study, $\overline{T}_{SK}$ dropped approximately $1.67°C \cdot hr^{-1}$ in waves, and $1.33°C \cdot hr^{-1}$ in waves for immersion suit B (Steinman et al., 1987). The $\overline{T}_{SK}$ of the participants in the current study dropped at a rate of $1.74°C \cdot hr^{-1}$ in the Weather 2 condition.

Tipton reported that immersions in conditions with wind, waves, and simulated rain reduced expected survival time by up to 30% compared to calm water tests (Tipton, 1991). The results of the current study do not agree with these findings as no significant differences in the change of deep body temperature were measured. Several differences in the immersion conditions in the current study and those used by Tipton may explain the discrepancies in the results. The immersion conditions used by Tipton were much more severe compared to the current study. Tipton’s participants performed four hour immersions in 4°C water, with periodic spraying of water at the same temperature. The significantly lower water temperature in the study by Tipton compared to that used in the present study (~ 11°C) created a much larger thermal gradient, which would lead to a greater amount of heat flow. As well, both suits used by Tipton experienced a significant amount of water leakage, with one suit (A) accumulating an average of 1.32L, and 2.2L in the other (B) (Tipton, 1991). Earlier studies have shown that the addition of water underneath the immersion suit will decrease suit insulation (and thereby reducing predicted survival time) (Hall and Polte, 1956; Allan et al., 1985; Light et al., 1987). The amount of water it takes to reduce insulation can be quite small as work by Hall and Polte, and Tipton and Balmi have shown that as little as 500mL of water underneath an immersion suit can decrease insulation between 20-30% (Tipton and Balmi, 1996). The participants in the current study had no water ingress into their suits and remained completely dry throughout all immersions. Given the amount of water that leaked into the suits of the participants in the study by Tipton, and the colder water temperatures used, it is not unexpected that those participants experienced a drop in deep body temperature, and those in the current study did not. That is, the conditions of Tipton were uncompensable and moved the participants outside of their “thermoregulatory zone”.

5.5.1 Implication for Future Studies.

Even with the immersion duration extended to three hours, no significant changes in deep body temperature were measured, and the increased thermal stress placed on the thermoregulatory system of the participants due to wind and waves was easily compensated for. $\dot{V}O_2$ values at the end of the immersions were well below the reported values associated with high levels of shivering in other studies ($1.14 L \cdot min^{-1}$) (Tipton 1991), and with no significant differences measured between the immersion conditions, the participants compensated for the increased heat flow most probably by reducing peripheral blood flow, leading to lower $\overline{T}_{SK}$.

The conditions of the current study were not sufficient to cause a significant drop in the deep body temperature of the participants. The combination of high insulation values of the suits used with the temperature of the water and air created a level of heat flow that was easily compensated for by the thermoregulatory system. Reducing the insulation value of the immersion suit, or testing in colder water and air temperatures, should result in a larger amount of heat flow that may not be compensated for by the thermoregulatory system.

The two Weather conditions used in this study significantly reduced the amount of insulation provided by the suit compared to Calm (Figure 5.6). Between the two Weather conditions, there was no significant difference in clo value, even though Weather 2 had faster wind speeds and higher wave heights. Given the lack of significant difference in clo value between the two

Weather conditions, it is unlikely that using wind speeds and wave heights greater than those used in Weather 2 would result in a significant reduction in clo value due to increased convective heat flow. The water velocity due to wave motion was $0.71 m \cdot s^{-1}$ in Weather 1, and $1.32 m \cdot s^{-1}$ in Weather 2 [5]. These water velocities are near, and in excess of the $0.75 m \cdot s^{-1}$ value reported by Witherspoon and colleagues in which heat flow values remain constant as water velocity increases (Witherspoon et al., 1971). While larger wave heights and faster wind speeds than those used in the current study would have increased water and air velocity over the participants, it is unlikely that this would have resulted in an increase in MSHF. As well, the heights of the waves used in the Weather 2 condition were near the maximum capability of the OEB to generate.

The clo value of an immersion suit is lowered by the addition of water underneath it as reported by Light and colleagues, and Tipton and Balmi (Light et al., 1987; Tipton and Balmi, 1996). Water leakage into an immersion suit has been reported in recent marine accidents (MRSC, 2008; TSB, 2010) and current CGSB testing standards assume that water leakage into an immersion suit will occur (CGSB, 2005). The current study measured the effect of wind and waves on human thermal responses while they were dry inside the suit, but it is not known if the impact that weather conditions have change when the humans are wet underneath the immersion suit. As insulation decreases, the increase in heat flow due to wind and waves might move individuals out of their thermoregulatory zone. As reported by other authors, one way insulation can decrease is due to water leakage under an immersion suit. The effects of wind and waves on human thermoregulatory responses while participants were wet underneath the immersion suits (Study 3) are described in Chapter Six.

In conclusion, the addition of wind and waves will cause a significant incremental increase in MSHF compared to calm water, but this effect may be compensated for by the human thermoregulatory system in relatively mild conditions.

[5] Wave particle/water velocity was calculated according to the formulae described in Table 4.1 from Sarpkaya, T. and Isaacson, M. (1981). *Mechanics of wave forces on offshore structures*. Van Nostrand Reinhold Company.

Chapter 6 - Study 3: Effects of Varying Wind and Wave Conditions on Human Thermoregulatory Responses with 500mL of Water Underneath the Immersion Suits.

6.1 Introduction.

In the previous two studies it was found that immersions in wind and wave conditions significantly increased MSHF compared to calm water. In the conditions tested in Studies 1 and 2, this increase in MSHF did not result in a significant decrease in deep body temperature. The increase in MSHF was compensated for by the thermoregulatory system of the participants most probably through vasoconstriction resulting in a fall in $\overline{T}_{SK}$, and with only small increases in metabolic heat production through shivering. The "warm" water and air temperatures (11°C and 17°C respectively), and the high level of insulation provided by the immersion suit allowed (2.05 clo in calm water) resulted in a compensable level of thermal stress that the thermoregulatory system responded with little strain as evidenced by the low $\dot{V}O_2$ values.

The total insulation provided by an immersion suit, and the clothing worn underneath it, can be reduced by water leakage. Allan and colleagues reported a 30% loss of insulation in uninsulated immersion suits when 500mL of water was added underneath them, over the chest and back of the participants (Allan et al., 1985). Work by Light and colleagues has shown that approximately 500mL of water leakage into an uninsulated immersion suit can result in an approximate 30% drop in insulation (Light et al., 1987). With 1.71 L of water in another type of uninsulated immersion suit, total insulation was reduced by 50% (Light et al., 1987). Later work by Tipton and Balmi investigated the effect that 500mL of water leakage underneath uninsulated immersion suits had on human thermoregulatory responses (Tipton and Balmi, 1996). They reported that 500mL of water applied over the limbs produced a rate of fall in rectal temperature equivalent to that seen with no leakage ($0.4°C·hr^{-1}$) , while 500mL applied over the torso resulted in a significantly faster rate ($0.55°C·hr^{-1}$) (Tipton and Balmi, 1996). The results from the work of Tipton and Balmi show that while water leakage can indeed be detrimental to the overall insulation value of the immersion suit, *where* this leakage occurs is also a significant factor.

Water leakage into immersion suits is an all too common occurrence, and current CGSB standards assume that it will occur and accounts for it during standards tests (CGSB, 2005). In

February 2008, the *Check Mate III* capsized off the North East Coast of Newfoundland, Canada and the two crew that abandoned ship into the water wearing immersion suits were dead in less than two hours. The follow up search and rescue report said that the immersion suits of the two crew members were completely filled with water when the fast rescue craft recovered them (John's, 2008). In March 2009, the helicopter immersion suit of the sole survivor of the Cougar Flight 491 crash was filled with water when they were recovered (TSB, 2010).

The previous work by authors that have investigated the effects of wind and waves on human thermoregulatory responses has been discussed in Chapters 4 and 5. The results from Studies 1 and 2 showed that wind and waves will significantly increase heat flow compared to calm water. It was yet to be established the effects wind and waves had on thermoregulatory responses with water leakage underneath the immersion suit. The aim of Study 3 was to build upon the results of the previous two studies and investigate the effect that 500mL of water applied over the torso would have on human thermoregulatory responses in wind and waves.

6.2 Hypothesis.

It was hypothesized that:

H_{01}: With 500mL of water underneath the immersion suit, there will be no significant difference in the change in deep body temperature between immersions in calm water and those in conditions with wind and waves.

H_{A1}: With 500mL of water underneath the immersion suit, the reduction in deep body temperature will be significantly greater in immersion conditions with wind and waves compared to calm water.

6.3 Methods.

This study was approved by NRC's REB (#:2009-67). Twelve healthy males volunteered for the study, and gave their written consent before participating. Three of participants from Study 2 returned for Study 3; the other nine were new. The physical characteristics of the participants are given in Table 6.1.

Table 6.1. Physical characteristics of the Study 3 participants (Mean [SD], *n* =12).

	Age	**Height (cm)**	**Mass (kg)**	**Body Fat %**	**Surface Area (m^2)**
Mean [SD]	25.6 [5.6]	181.0 [4.7]	82.7 [10.2]	18.8 [3.1]	2.0 [0.2]
Range	19.0 – 34.0	175.0 – 192.0	70.1 – 101.4	14.6 – 22.8	1.9 – 2.3

Study 3 consisted of three separate data collection sessions, separated by at least 48 hours. Participants wore a similar clothing ensemble to that worn in Study 2, which is based on CGSB testing standards (CGSB, 2005). All clothing was provided to the participants to standardize the ensembles across test conditions. The participants wore an external bladder similar to that used in Study 2 with some modifications. Instead of the condom catheter inserted into the Travel John disposable urinal (Reach Global Industries, Irvine, CA, USA), it was attached to a medical grade urine collection bag. The Travel John powder was put into the urine collection bag to solidify, deodorize, and sanitize any urine. Participants performed three separate, 3-hour immersions in the conditions listed in Table 6.2

Table 6.2. Immersion conditions for Study 3

Condition	**Max Wave Height (m)**	**Mean Wind Speed ($m \cdot s^{-1}$)**	**Mean Water Temperature [SD] (°C)**	**Mean Air Temperature (SD) (°C)**
Calm	0	0	8.5 [0.9]	16.6 [0.7]
Weather 1	0.34	3.5	8.3 [0.6]	16.7 [0.5]
Weather 2	0.67	4.6	8.5 [0.5]	16.7 [0.5]

6.3.1 Procedure.

A counterbalanced Latin Square design was used to determine the order of the immersions for each participant. The procedure for each participant was similar to that outlined in Study 2, with the exception of the application of the 500mL of water underneath the immersion suit. After the participants were instrumented, clothed, and had partially donned the immersion suit they proceeded to the test area. At the test area, 500mL of water was weighed out evenly into two separate spray bottles (250mL in each). The participant held the partially donned immersion suit around their waist and two members of the research team applied the room temperature water to the front and back of the torso of the participant. The water was applied evenly over the front and back of the torso, from the waist up to the shoulders of the participant. Both spray bottles were completely emptied over the participants, with any excess water runoff falling into the immersion suit as it was held around their waists. The 500mL of water completely saturated the shirts worn by the participants. After the water was applied, the participants fully donned the immersion suit and proceeded to the test location. Once at the test location, the participants inserted their earphones, the data acquisition systems were checked for functionality, and five minutes of baseline data were collected. After the baseline data were collected, the participant proceeded down the stairs into the water where they remained submerged up to the neck for two minutes. After the two minutes, the participants exited the water and dripped dry for one minute, and were then weighed on a M200 Digital Weight Indicator platform scale (Western Scale Co. Limited , Port Coquitlam, B.C., Canada). This mass was recorded as the pre-immersion mass. After the weighing, the participants looped their feet through the taigon tubing tether used in Study 2, and were manoeuvred into the test position. The participants were able to watch and listen to movies in the same method, as they were able to in Study 2.

After the immersion was completed, the participant exited the water and was allowed to drip dry for one minute. The participant was then weighed a second time on the same scale as before and this mass was recorded as the post-immersion mass. The pre-immersion mass was subtracted from the post-immersion mass to ensure that no additional water leaked into the immersion suit. This method for determining water ingress was based on CGSB testing standards (CGSB, 2005).

The data were downloaded from the acquisition systems, and the participants were subsequently de-instrumented and rewarmed in a bath of 40°C water. Once the deep body temperature of the participants approached pre-immersion values, they exited the bath and dressed in their street clothing. Participants were offered hot beverages and snacks and once their well being was assured, they were allowed to leave the facility to return for their next scheduled test.

6.3.2 Data Analyses.

The same data analyses procedures used in Study 2 were used in Study 3.

6.3.3 Statistical Analyses.

The same statistical analyses procedures used in Study 2 were used in Study 3. A between group comparison (unpaired t test) was performed when comparing the results from Study 2 to Study 3.

6.4 Results.

Two participants only completed 90 minutes in the Weather 2 condition. As a result, the data for these two participants are not included in any subsequent analysis. The values reported from the gastro-intestinal pills of two participants were considered suspect and were not included in the analysis of deep body temperature. After completing a test, one participant reported consuming a large volume of hot liquid prior to the start of the test. Another participant still retained the pill six days after initially ingesting it. A retrospective power calculation was performed and a sample size of n = 8 was sufficient for reporting results at with 80% power.

6.4.1 Baseline Values.

The baseline values for T_{GI}, $\overline{T}_{SK}$, MSHF, and $\dot{V}O_2$ are presented in Table s 6.3-6.5

Table 6.3. Study 3 Calm condition baseline values for T_{GI}, $\overline{T}_{SK}$, MSHF, and $\dot{V}O_2$ (n = 10).

	T_{GI} (°C)	$\overline{T}_{SK}$ (°C)	MSHF ($W \cdot m^{-2}$)	$\dot{V}O_2$ ($L \cdot min^{-1}$)
Mean [SD]	37.41 [0.29]	31.93 [0.46]	61.48 [4.55]	0.340 [0.092]
Range	36.98 - 37.86	31.42 - 32.67	54.98 - 69.96	0.257 - 0.560

Table 6.4. Study 3 Weather 1 condition baseline values for TGI, T̄ SK , MSHF, and V̇O2 (n = 10).

	T_{GI} (°C)	$\bar{T}_{SK}$ (°C)	MSHF ($W \cdot m^{-2}$)	$\dot{V}O_2$ ($L \cdot min^{-1}$)
Mean [SD]	37.36 [0.24]	31.56 [0.41]	62.94 [4.51]	0.311 [0.043]
Range	37.03 - 37.84	30.74 - 32.25	56.57 - 70.87	0.260 - 0.415

Table 6.5. Study 3 Weather 2 condition baseline values for T_{GI}, $\bar{T}_{SK}$, MSHF, and $\dot{V}O_2$ (*n* = 10, * = *n* = 8).

	T_{GI} (°C)*	$\bar{T}_{SK}$ (°C)	MSHF ($W \cdot m^{-2}$)	$\dot{V}O_2$ ($L \cdot min^{-1}$)
Mean [SD]	37.45 [0.26]	31.96 [0.81]	61.31 [4.51]	0.339 [0.74]
Range	37.04 - 37.83	30.88 - 33.67	53.16 - 67.77	0.237 - 0.482

6.4.2 Water Leakage.

Participants weighed an average of 130g less after immersions in the Calm condition; 30g less after Weather 1; and 130g more after Weather 2. It is unlikely that the 130g of water leaked into the immersion suits during Weather 2 for several reasons. First, no participant reported feeling any water ingress into the suit during the tests. Second, the immersion suits used in Study 3 were the same used in the previous two studies, and no water leakage was observed during the previous studies. Thirdly, the White's immersion suit has pockets designed to contain excess suit fabric that may result when shorter individuals wear it. The wave heights in Weather 2 were sufficiently large enough to wash over the participants while they were in the water, and likely deposited water in these pockets over the three hour period.

6.4.3 Mean Skin Heat Flow.

Compared to Calm (79.45 [9.19]$W \cdot m^{-2}$), MSHF was significantly greater in Weather 1 (102.06 [11.98]$W \cdot m^{-2}$) and in Weather 2 (107.48 [3.63]$W \cdot m^{-2}$). There were no significant differences in MSHF between the two weather conditions.

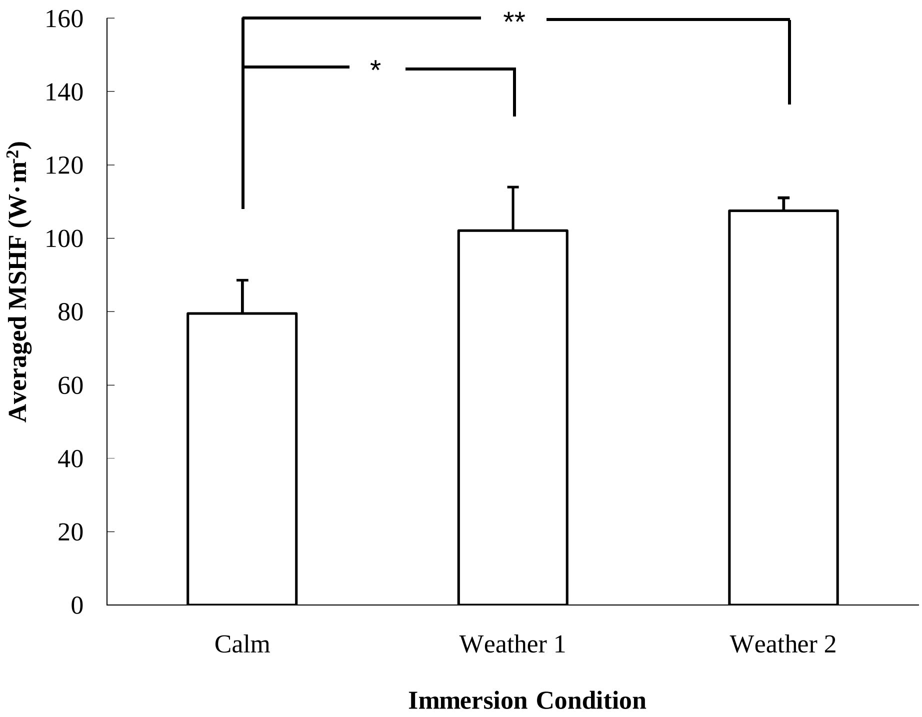

Figure 6.1. Averaged MSHF ($W \cdot m^{-2}$)at the end of the three hour immersions. (Mean [SD], n = 10, * = $P < 0.05$, ** = $P < 0.001$).

6.4.4 Mean Skin Temperature Change

There was a significant difference in the change of $\overline{T}_{SK}$ between Calm (-4.27 [0.63]°C) and Weather 1 (-5.14 [1.11]°C). There was a significant difference in the change of $\overline{T}_{SK}$ between

Calm and Weather 2 (-5.78 [0.61]°C). There was no significant difference between the change in $\overline{T}_{SK}$ between Weather 1 and Weather 2.

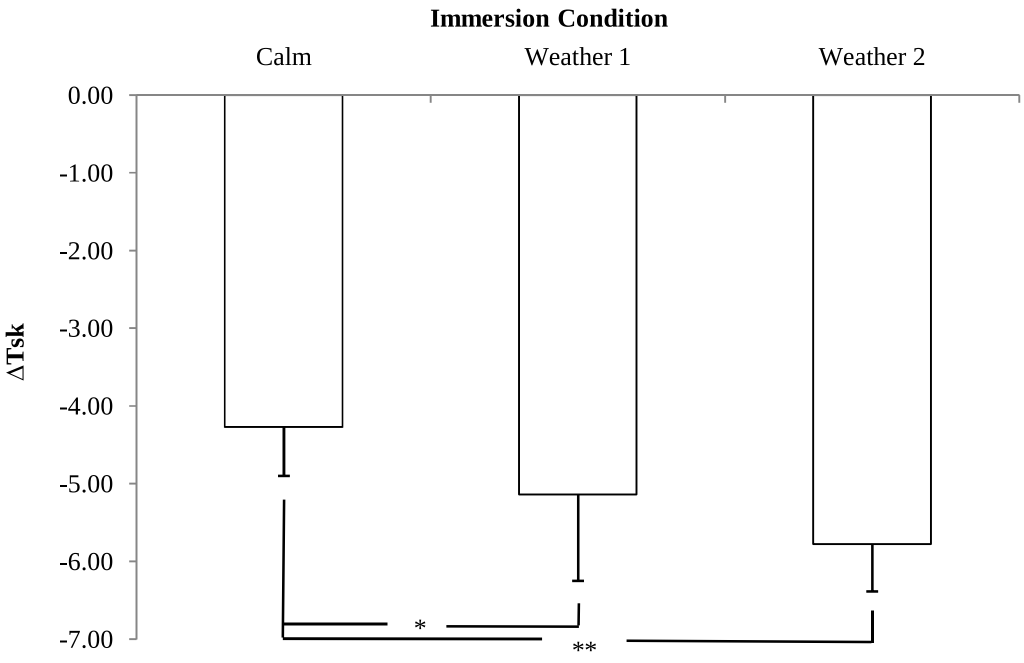

Figure 6.2. Change in $\overline{T}_{SK}$ (°C) over the course of the three hour immersions (Mean [SD], *n* = 10, * = P < 0.05, ** = P < 0.001).

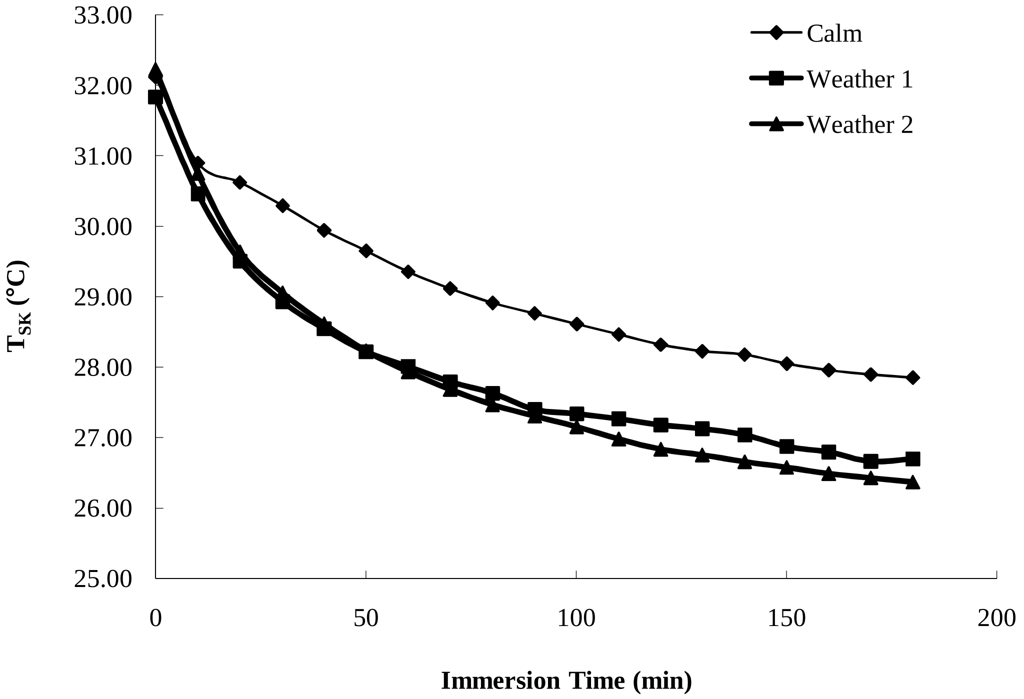

Figure 6.3. Absolute $\overline{T}_{SK}$ (°C) during the three hour immersions (*n* = 10, Average [SD] (°C) Calm: 0.61, Weather 1: 0.71, Weather 2: 0.93).

6.4.5 Gastro-intestinal Temperature Change.

There were no significant differences in the change of T_{GI} across all immersion conditions. The change in T_{GI} was -0.35 [0.14]°C in Calm; -0.38 [0.15]°C in Weather 1; and -0.29 [0.25]°C in Weather 2.

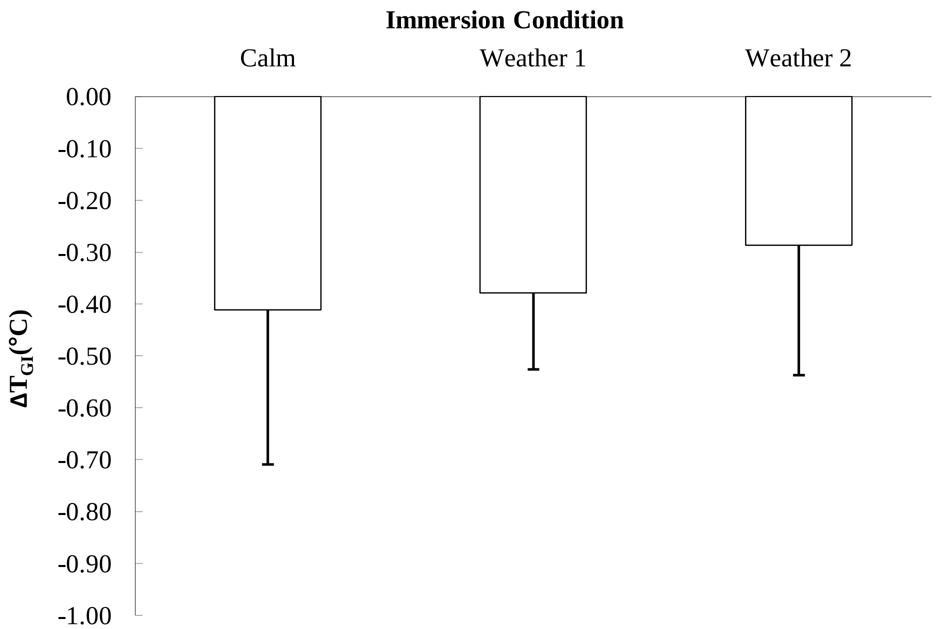

Figure 6.4. Change in T_{GI} (°C) over the course of the three hour immersions. (Mean [SD], *n* = 8).

The rate of change in T_{GI} (°C·hr^{-1}) during the last 30 minutes of the immersions is given in Table 6.6.

Table 6.6. Rate of change of T_{GI} (°C·hr^{-1}) during the last 30 minutes of the immersions (Mean [SD], *n* =8).

	Calm	**Weather 1**	**Weather 2**
T_{GI} Change (°C·hr^{-1})	-0.09 [0.13]	-0.12 [0.16]	-0.04 [0.18]

Body fat percentage significantly correlated with change in T_{GI} in the Weather 1 condition. For the Calm and Weather 2 conditions, there were no significant correlations (Table 6.7).

Table 6.7. Correlation coefficients (r values) between body fat percentage and change in T_{GI} in Study 3 (n = 8, * = $P < 0.05$).

	Calm	**Weather 1**	**Weather 2**
Body Fat %	-0.63	0.78*	-0.22

6.4.6 $\dot{V}O_2$ During the Last 30 Minutes of Immersion.

There were no significant differences in the measured $\dot{V}O_2$ values during the last 30 minutes of the immersions. $\dot{V}O_2$ in the Calm condition was 0.449 [0.054]$L \cdot min^{-1}$; 0.503 [0.051]$L \cdot min^{-1}$ in Weather 1; and 0.526 [0.120]$L \cdot min^{-1}$ in Weather 2.

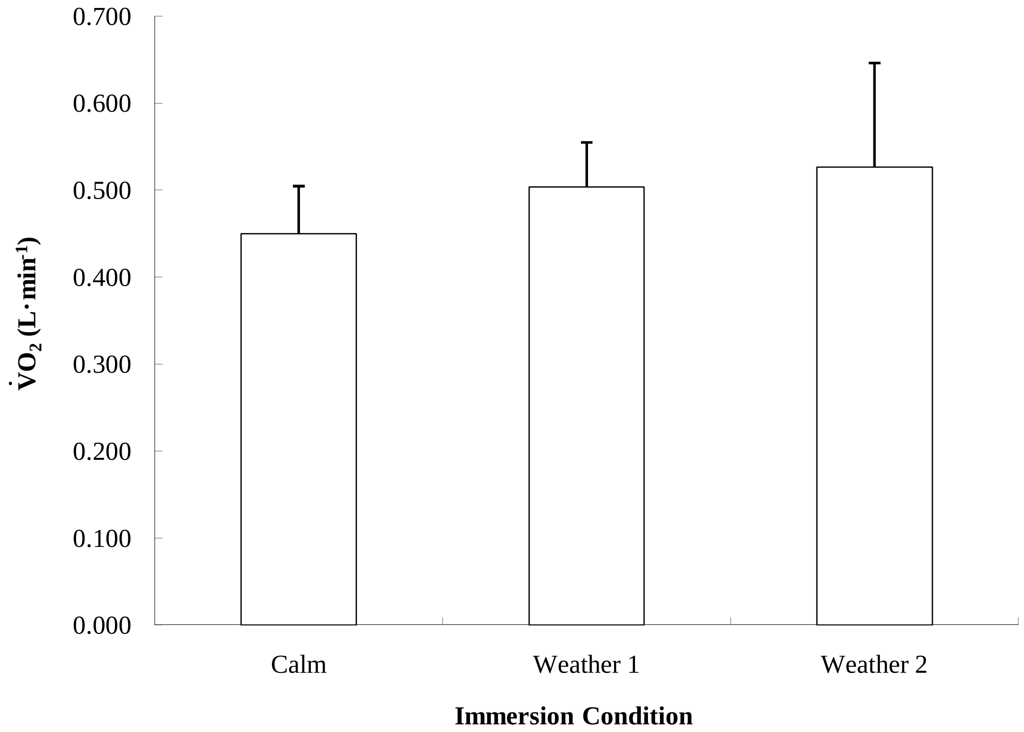

Figure 6.5. $\dot{V}O_2$ ($L.min^{-1}$) during the last 30 minutes of immersion. (Mean [SD], n = 10).

6.4.7 Clo Value.

Clo values were significantly lower in both Weather conditions compared to Calm. There was no significant difference in the clo values between the two Weather conditions. The clo value in Calm was 1.5 [0.2]clo; in Weather 1 it was 1.2 [0.1]clo; and in Weather 2 it was 1.1 [0.1]clo.

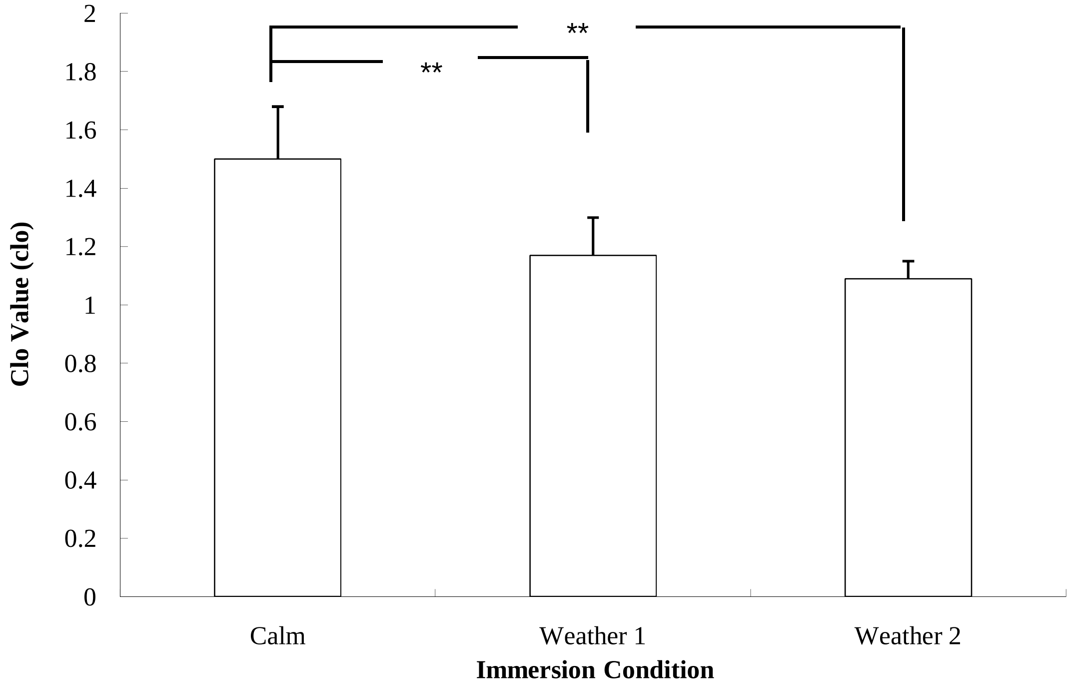

Figure 6.6. Clo value at the end of the three hour immersions. (Mean [SD], *n* = 10, ** = P < 0.001).

6.4.8 Increase in Heat Flow From Calm Water – Dry vs. Wet.

The MSHF values from the participants in Study 2 ("Dry" group) were compared to those in Study 3 ("Wet" group). There were no significant differences in the increase in MSHF when moving from Calm water to Weather conditions between the dry group of participants and the wet group (Figure 6.7). For the dry group of participants (Study 2), MSHF increased (compared to Calm water) by 17.6 [5.6]% in Weather 1; and 20.5 [6.0]% in Weather 2. For the wet group of participants, MSHF increased (compared to Calm water) by 21.3 [12.2]% in Weather 1; and 26.0 [9.0]% in Weather 2

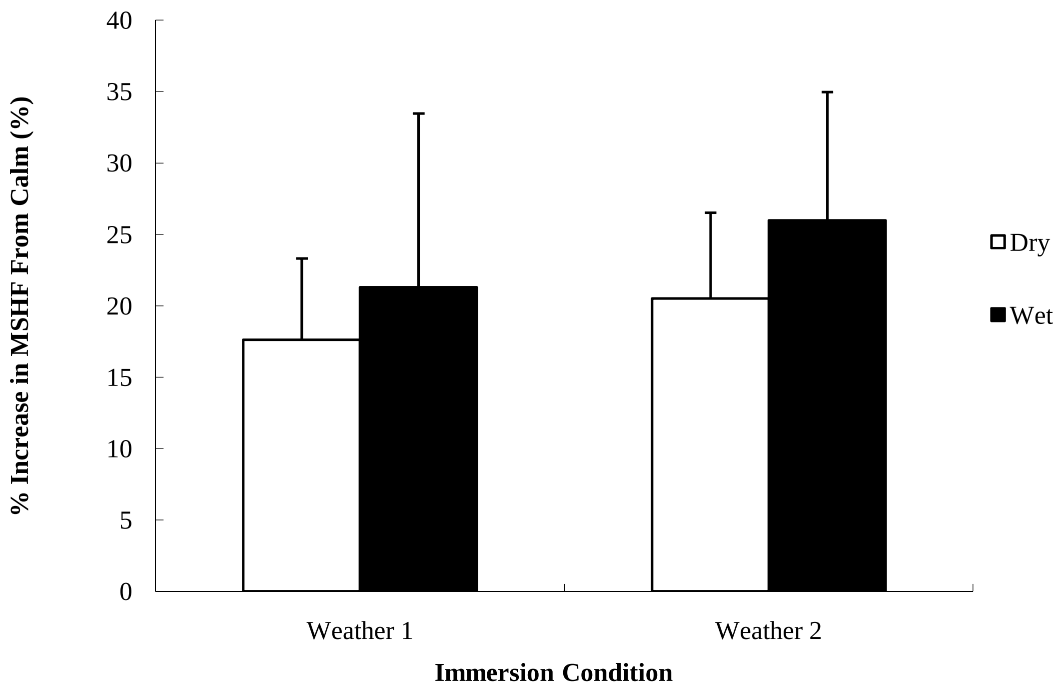

Figure 6.7. Increase in averaged MSHF compared to the Calm condition for the Dry and Wet participants. (Mean [SD], n = 12 for "Dry"; n = 10 for "Wet.).

6.5 Discussion.

The null hypothesis is accepted: with 500mL of water underneath the immersion suit, there were no significant differences in the decrease in deep body temperature between Calm and the two Weather conditions.

The results from this experiment concur with the previous two studies (Studies 1 and 2): immersions in wind and waves will significantly increase MSHF compared to calm conditions. In order to compare the MSHF between Studies 2 and 3 MSHF was re-calculated[6] to account for the different water temperatures. The MSHF measured in the current study (wet underneath the immersion suit) was greater than Study 2 (dry underneath the immersion suit) for all conditions; MSHF was 20% greater in Calm; 25% greater in Weather 1; and 26% greater in Weather 2. As a result, MSHF was 20% greater with 500mL of water underneath the immersion suit when re-calculating for the water temperature difference between the two studies.

Even though the MSHF was greater with 500mL of water underneath the immersion suit, this did not result in any significant differences in the decrease in T_{GI} across all immersion conditions; a similar finding to that of Study 2. Unlike the previous study, immersion $\dot{V}O_2$ values (Figure 6.5) were significantly greater than baseline measurements. This increase in $\dot{V}O_2$ values during the immersion reflects the greater amount of thermal stress placed on the participants by the addition of 500mL of water underneath the immersion suits. Even with the increase in MSHF in the Weather 2 condition, the thermoregulatory system was able to compensate for this increased thermal stress and maintain a relatively stable deep body temperature within the thermoregulatory zone. That is, the thermal stress was compensable and the participants thermoregulated.

[6] MSHF was recalculated by rearranging the equation described in section 3.5.5 for calculating clo value. Knowing the clo value of the immersion suit and the $\overline{T}_{SK}$ of the participant, MSHF can be calculated for a given water temperature.

The significant positive correlation between change in T_{GI} and body fat percentage in Weather 1 is supported by earlier work by Hayward and Eckerson (1984), in which skin fold thickness negatively correlated with the rate of fall of rectal temperature, however it is likely that this is a spurious result as it was not seen in Weather 2, and T_{GI} was not really falling far or fast enough for subcutaneous fat to be critical. There were no significant differences in MSHF; $\overline{T}_{SK}$; T_{GI}; and $\dot{V}O_2$ between the Weather 1 and 2 conditions (Figures 6.1, 6.2, 6.4, and 6.5). This suggests that the thermal stress (MSHF) was equivalent between the two conditions, the participants responded the same ($\overline{T}_{SK}$ and T_{GI}) with a similar amount of effort ($\dot{V}O_2$), but there was no significant correlation between body fat percentage and change in T_{GI} in Weather 2. The lack of a similar correlation in a condition with an equivalent level of thermal stress, and subsequent participant response to that stress, would suggest that the Weather 1 correlation is a random occurrence.

To compare the oxygen consumption rates between the Study 2 (dry) and 3 (wet) participants' $\dot{V}O_2$ were normalized by their mass (kg) ($mL \cdot kg^{-1} \cdot min^{-1}$). It was significantly higher for the group of wet participants in each immersion condition compared to the participants who were dry underneath their suits (Figure 6.8). The addition of 500mL of water underneath the immersion suit increased the amount of heat flow to the external environment compared to being dry (Study 2), but the Study 3 participants were able to compensate for this by increasing their metabolic heat production. Even though the presence of 500mL of water underneath the immersion suit significantly increased $\dot{V}O_2$, the participants were not close to their maximum shivering ability. Tipton (1991) reported a $\dot{V}O_2$ of $1.14 L \cdot min^{-1}$ for shivering associated with an inability to stabilize the rate of fall of deep body temperature during immersions in turbulent conditions.

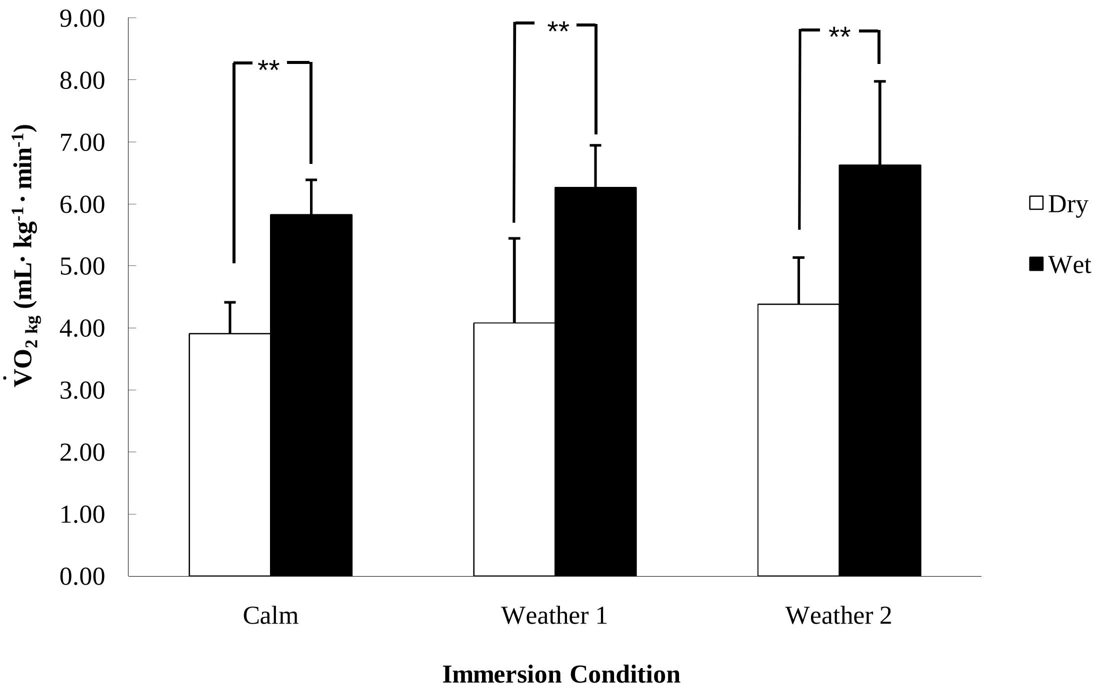

Figure 6.8. $\dot{V}O_{2\ kg}$ (mL.kg^{-1}.min^{-1}) for the Dry and Wet groups of participants. (Mean [SD], "Dry" = no water underneath immersion suit (Study 2); *n* = 12, "Wet" = 500mL of water underneath immersion suit; *n* = 10, ** = p < 0.001).

The $\dot{V}O_2$ values reported by Tipton and Balmi (1996) were higher than those measured in the current study. When 500mL of water was applied to the torso of the participants immersed in 10°C agitated water in their study, Tipton and Balmi reported a mean $\dot{V}O_2$ of ~ 0.800L·min^{-1} during the last 20 minutes of the tests. In the current study, the participants had a mean $\dot{V}O_2$ of 0.526L·min^{-1} in Weather 2; a condition with wind and waves that the tests in the study by Tipton and Balmi did not have. The lower $\dot{V}O_2$ values measured in the current study compared to those reported by Tipton and Balmi can be attributed to the lower clo value of the clothing worn by their participants. Tipton and Balmi (1996) reported an external clo value of approximately

0.50clo with 500mL of water applied to the torso of their participants, which was lower than the clo value of 1.09 in Weather 2 in the current study. The lower clo value in their study resulted in a larger MSHF (~150$W \cdot m^{-2}$ for the abdomen; ~250$W \cdot m^{-2}$ for the back) (Tipton and Balmi, 1996) compared to the current study (107$W \cdot m^{-2}$ for the whole body in Weather 2).

In the current study (i.e. with leakage), the clo value of the immersion suits were reduced by approximately 20% in each immersion condition compared to the values measured in Study 2. Previous work by other authors has reported a greater decrease in clo values with 500mL of water underneath an immersion suit. Allan and colleagues reported a reduction in clothing insulation of approximately 30% for three separate style immersion suits when 500g of water was applied to the front and back of their participants (Allan et al., 1985). Light and colleagues reported a similar reduction of about 30% in clothing insulation when approximately 500g of water was present underneath the immersion suits in their study (Light et al., 1987). A 30% reduction in Clo value was also reported by Tipton and Balmi when 500g of water was applied over the torsos of their participants during immersions. (Tipton and Balmi, 1996). An explanation for the smaller reduction in clo value in the current study compared to the results reported by the authors of the previous studies is the style of immersion suits used. Allan and colleagues, Light and colleagues, and Tipton and Balmi, all used *uninsulated* immersion suits, which are a water-proof shell worn over clothing. The insulation in these suits was provided by the under clothing, usually in the form of a one-piece woollen or synthetic “Woolly Bear” or standard clothing. In the current study, the immersion suits used closed cell neoprene foam to provide insulation, and relied less on the undergarments worn. Closed cell neoprene foam will not lose as much of its insulative properties when wet compared to the underclothing worn by the participants in the studies by the other authors. As a result, in the current study, there was less of a drop in clo value measured when the same amount of water used in studies by other authors was added underneath the immersion suit.

6.5.1 Implications for Future Studies.

The addition of 500mL of water underneath the immersion suit resulted in a significantly lower clo value compared to remaining dry (Figure 6.6). The reduction of the clo value of the immersion suit is a consequence of the increase in MSHF compared to when dry. In the context of the current study, this increase in MSHF did not result in a significant drop in deep body temperature. The participants in the current study were able to compensate for this increase in MSHF by increasing heat production via shivering, as indicated by their significantly greater $\dot{V}O_2$ values compared to a group that were dry inside their immersion suits (Figure 6.8).

The addition of the water underneath the immersion suits resulted in a greater strain on the thermoregulatory system of the participants as indicated by the increased $\dot{V}O_2$. Other authors (Hall and Polte, 1956; Allan et al., 1985; Light et al., 1987; Tipton and Balmi, 1996) have reported that water leakage underneath the immersion suit over the torso results in significant reductions in predicted survival times, due to the increased MSHF and a faster fall in deep body temperature, if the increased thermal stress is not compensable. In the current study, the addition of 500mL of water underneath the immersion suit did significantly increase heat flow compared to when dry (in agreement with studies by other authors), but did not result in a significant fall in deep body temperature (not in agreement with other authors). Water leakage under an immersion suit will only result in a significant fall in deep body temperature (compared to when dry) if this increased thermal stress is not compensable by the thermoregulatory system.

Performance of immersion suits can be significantly over-estimated if leakage tests during the certification process are not rigorous enough. The current IMO LSA code requires that the leakage tests for immersion suits only require a jump from a sufficient height to completely submerge a person, float in *calm water* for only one hour, and a 20 minute swim in calm water (IMO, 2010). The current edition of the Canadian General Standards Board (CGSB) standard for Immersion Suit Systems (CAN/CGSB 65.16-2005) require a similar set of tests to calculate water leakage into the immersion suit. Work by the CORD Group Ltd. has shown that this method of measuring water ingress will significantly underestimate the amount of water that could possibly leak into an immersion suit during more realistic test conditions (CORD, 2009). Immersions in simulated storm conditions (wind and waves) resulted in 2633 ± 1609mL of water leakage into a face seal style suit, compared to the 1048 ± 548mL calculated from calm water trials as prescribed by CGSB standards (CORD, 2009). Water leakage underneath the immersion suit increases the thermal stress placed on the individual and increases MSHF, causing increased strain on the thermoregulatory system in order to compensate for the increased heat loss (Figure 6.8). The underestimation of water leakage into an immersion suit can lead to an overestimation of performance. A suit may have little to no water ingress during tests in calm water pools, and as a result, allow a person to successfully thermoregulate during the thermal tests and prevent hypothermia from occurring. More realistic conditions (wind, waves, wind driven spray etc.) may challenge the water tight integrity of the same suit and result in water leakage. With a reduction in suit insulation due to the water leakage, and resulting increase in MSHF, participants may be unable to compensate for the increased thermal strain, resulting in a drop in deep body temperature and an increased risk of hypothermia and death.

In conclusion, the addition of 500mL of water under an immersion suit significantly increased MSHF compared to when it was dry inside. This heat flow is further increased by the addition of wind and waves to the immersion conditions. This increased heat flow may be compensated for (depending on water temperature and suit type), but this increased thermal strain should be accounted for during any certification tests.

Chapter 7 - Change in Predicted Survival Times Due to Wind and Waves

7.1 Survival Time Predictions.

The results from the three studies presented in this thesis show that wind and waves will significantly increase MSHF compared to immersions in calm water. In the studies, all participants were able to thermoregulate in the conditions tested and thereby maintain a stable deep body temperature, even with the significantly increased MSHF due to wind and waves. The high level of insulation provided by the immersion suit and the relatively high temperatures of the air and water in the test conditions were sufficient to enable thermoregulation. Lower temperatures and lower clothing insulation values would have resulted in more significant changes in deep body temperature in the wind and wave conditions compared to calm water.

Computer modeling is one method for determining if at colder temperatures and lower clothing insulation values, wind and waves would cause significant reductions in deep body temperature compared to calm water. The anthropometrics of a person, the clothing worn by them, and the environmental conditions are entered into the program and an estimated survival time is generated based on these inputs (Keefe and Tikuisis, 2008). Two separate software programs have traditionally been used to predict survival time for immersed persons with a falling deep body temperature: the Wissler model (Wissler, 1985), and the Cold Exposure Survival Model (CESM). The CESM is a software program developed to predict the survival time of individuals exposed to cold conditions (Tikuisis, 1997; Keefe and Tikuisis, 2008). It predicts the amount of time it will take for a person's deep body temperature to drop to the lethal level of 28°C (Keefe and Tikuisis, 2008); a temperature that is associated with the onset of ventricular fibrillation and subsequently death (Golden, 1973).

Survival time predictions were generated for the two groups of participants from Studies 2 and 3 (Appendix A). The Study 2 participants had no water underneath their immersion suits ("Dry"), while the Study 3 participants had 500mL of water underneath their suits ("Wet"). The predicted survival times for both groups of participants are given in Figure 7.1.

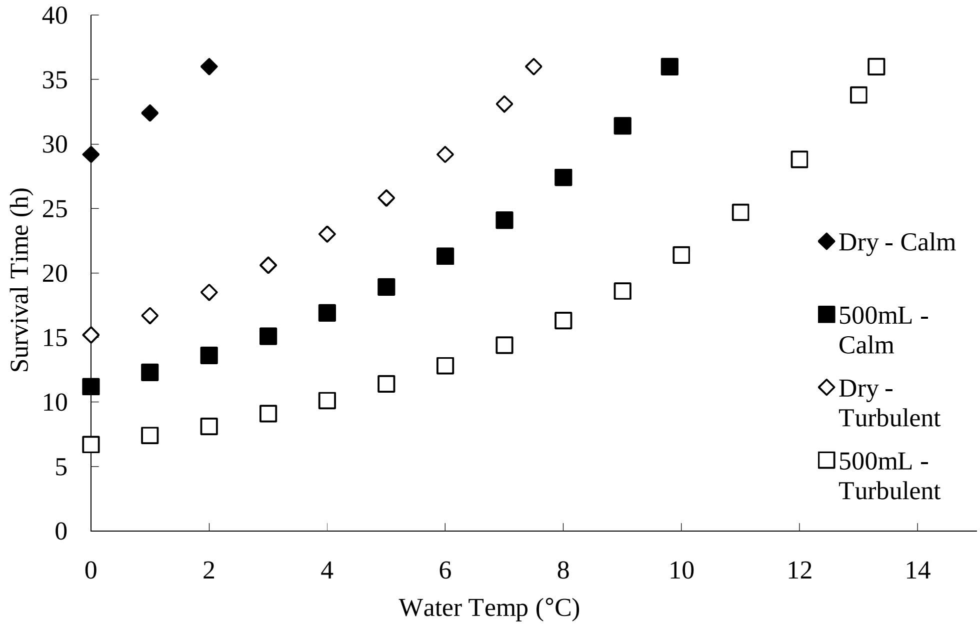

Figure 7.1. CESM predicted survival times (h) for two separate groups of participants. ("Dry" = no water underneath the immersion suits (*n* = 12); "Wet" = 500mL of water underneath the immersion suit (*n* = 12), "Turbulent" = wind and waves condition).

The maximum survival time prediction generated by the CESM is 36 hours, as it is assumed that after this time factors other than hypothermia will cause death (Keefe and Tikuisis, 2008).The CESM-predicted survival times (> 36 hours) for both groups of participants in the conditions of the present tests are in agreement with the lack of change in T_{GI} reported in Study 2. When the Study 2 participants ("Dry") were immersed in calm and wind and wave conditions there were no significant decreases in deep body temperature. The CESM-predicted survival times for the Study 2 participants in 11°C (mean water temperature in Study 2) were in excess of 36 hours for both the calm and wind and wave conditions.

The CESM-predicted survival times for the Study 3 participants ("Wet") were not in agreement with the reported results. The CESM-predicted survival times for the Study 3 participants in 8.5°C water (mean water temperature in Study 3), with 500mL of water underneath the immersion were approximately 27 hours in calm water, and approximately 16 hours in wind and wave conditions. No significant changes in deep body temperature were measured in Study 3 across all conditions, and while $\dot{V}O_2$ values were not close to maximum, they were significantly greater than those measured in Study 2 (Figure 6.8). This confirms that the 500mL of water "leakage" and colder water temperature resulted in more thermal stress on the participants, requiring a greater amount of physiological strain to thermoregulate and maintain a stable deep body temperature. If the immersions in Study 3 had been continued past three hours it is possible that the rate of fall in deep body temperature may have been different between Calm and the two weather conditions due to the increased heat flow.

The predicted survival times generated by the CESM for the water temperatures used in Studies 2 (11°C) and 3 (8.5°C) for both calm, and wind and waves conditions, are high (> 12 hours). It is not until the water temperature is 2°C and lower, that predicted survival times are less than 20 hours, and even then only for conditions where the participants are not dry inside their immersion suit in calm water. It is only in the "worst" immersion condition accounted for within the model (500mL of water inside the suit with wind and waves at 0°C water) that the predicted survival times of the participants are 6.7 hours. The CESM results show that wind and waves will reduce predicted survival times compared to calm water, which is not supported by the results of Studies 2 and 3. The results from Studies 2 and 3 shows that the addition of wind and waves will significantly increase MSHF, this did not translate into a significant fall in T_{GI}; the increased thermal stress was compensated for by the thermoregulatory system. In the conditions tested in Studies 2 and 3, the temperature of the water, and level of insulation provided by the immersion suits used, resulted in high predicted survival times (> 36h). The results from the CESM confirm that changing the water temperature or immersion condition (calm or turbulent) will increase the strain on the thermoregulatory system. For example, when individuals are dry and in calm water, the predicted survival time is near the maximum of 36 hours at 2°C (Figure 7.1). When wind and waves are added (turbulent condition), to achieve the same predicted survival time, the water temperature would need to be closer to 8°C (Figure 7.1). In this example, immersions in 2°C calm water induces the same level of strain on the thermoregulatory system as immersions in 8°C turbulent water. The same effect is observed with the predicted survival times when individuals are wet underneath the immersion suit. To achieve the same predicted survival time with water under the immersion suit, as when dry in 2°C calm water, the water temperature would have to be approximately 10°C. The predictions provided by the CESM suggest that if a person was wet under the immersion suit in turbulent water, in order to survive for more than 36 hours, the water temperature would have to be 13°C, or higher (Figure 7.1). Changing the water temperature, immersion conditions and level of water underneath the immersion suit will increase or decrease the thermal stress placed on the thermoregulatory system, influencing the amount of physiological strain a person experiences in maintaining a stable deep body temperature.

Current CGSB and IMO standards for immersion suits (CGSB, 2005; IMO, 2010) require that immersion suits prevent hypothermia from occurring in under six hours in calm, circulating 2°C water. However, the predicted CESM survival times (drop in deep body temperature to 28°C or lower) for individuals in 0°C water with wind and waves, and with 500mL of water underneath the immersion suit, is only slightly above that time (Figure 7.1). These CESM calculations illustrate the inherent danger of testing in conditions not representative of those found offshore with regards to over-estimating immersion suit performance, and under-estimating the strain placed on the thermoregulatory system. For example, during 2010 off the southeast coast of Newfoundland, Canada, the lowest monthly mean significant wave height measured was 1.66m, and the highest was 4.06m. Mean monthly wind speeds ranged from a low of $0.63 m \cdot s^{-1}$, to a high of $10.37 m \cdot s^{-1}$. The conditions off the east coast of Newfoundland, Canada are often far from the “calm, circulating” water prescribed in the CGSB and IMO standards for testing immersion suits.

The CESM results confirm that as either the temperature of the water decreases, or total insulation is reduced by weather conditions or water leakage, predicted survival times decrease as well. With decreasing water temperature, an increase in MSHF is expected as the thermal gradient between the participant and external environment increases. A reduction in insulation will also increase MSHF instantaneously, but that thermal gradient will soon be reduced as $\overline{T}_{SK}$ falls. As the MSHF increases, the strain on the thermoregulatory system in maintaining a stable deep body temperature will rise as well. When MSHF exceeds the maximum capabilities of the body to generate heat through shivering, heat debt will develop, leading to hypothermia and ultimately death.

7.2 Change in Clo Value.

Using data collected from Studies 2 and 3, the change in clo value moving from no water leakage inside an immersion suit while in calm water, to other immersion/test conditions were calculated (Figure 7.2).

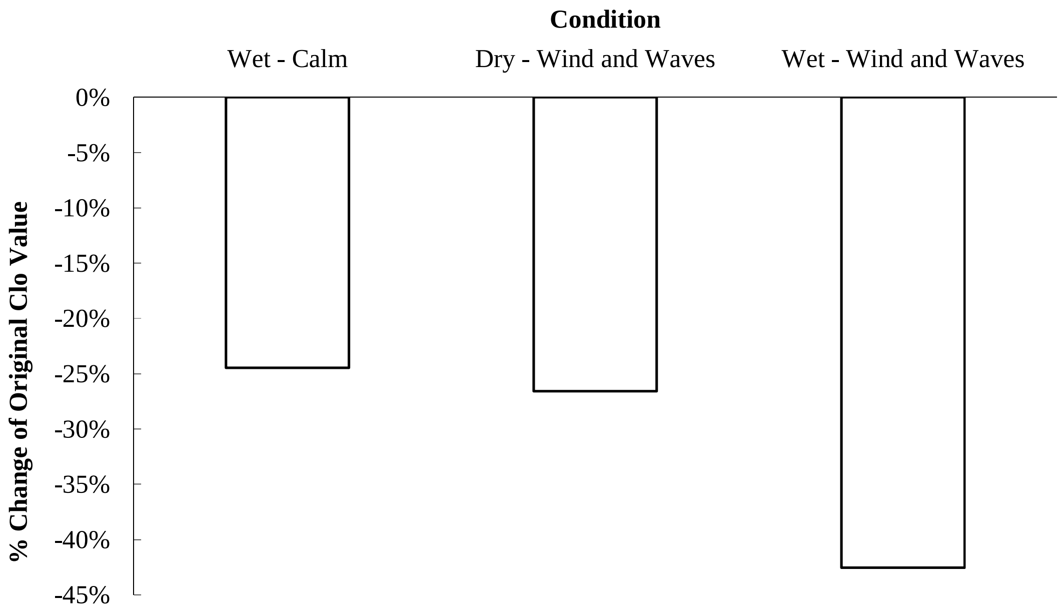

Figure 7.2. Percent change in clo value from calm water values in various immersion conditions. (“Wet” = 500mL of water underneath immersion suit).

The addition of 500mL of water underneath the immersion suit used in Study 3 resulted in a 24% drop in clo value (Fig 7.2: “Wet – Calm”) compared to calm, dry conditions. When dry inside the suit in wind and waves, clo value dropped by 27% (Fig 7.2: “Dry – Wind and Waves”) compared to calm conditions, which is in good agreement with the work by Romet and colleagues (1991) who found a mean decrease of 29.7% in suit insulation when moving from calm to turbulent water. The lack of significant differences in MSHF between the two weather conditions in Studies 2 and 3 suggest that the decrement in insulation can be regarded as a constant once a minimum water velocity has been achieved (*i.e.* sufficient to destroy the boundary layer). The greatest decrease in clo value was measured when the participants had 500mL of water underneath the immersion suit, and were immersed with wind and waves. This resulted in a 43%

decrease in clo value (Fig. 7.2: “Wet – Wind and Waves”) compared to calm conditions while dry inside the immersion suit.

7.3 $\dot{V}O_2$ Required to Maintain Thermal Balance.

In the three studies presented in this thesis, all participants were able to successfully thermoregulate, and prevent a fall in deep body temperature. By reducing the heat loss to the external environment by vasoconstriction and replacing any lost heat by metabolic heat production, the participants were able to match the heat flow and remain in thermal balance.

Figure 7.3 shows the $\dot{V}O_{2\ P}$ required by a person with a SA of 2.0m^2 to remain in thermal balance with the estimated heat loss in 0°C water across a range of $\overline{T}_{SK}$ and clo values[7]. It should be noted that the values used for $\overline{T}_{SK}$ are to establish the thermal gradient with the water to predict heat flow from a person, and are not meant to represent values that drive thermoregulatory responses such as shivering and vasoconstriction.

[7] Refer to sections 3.5.6 – 3.5.8 for the equations for $\dot{V}O_{2\ P}$

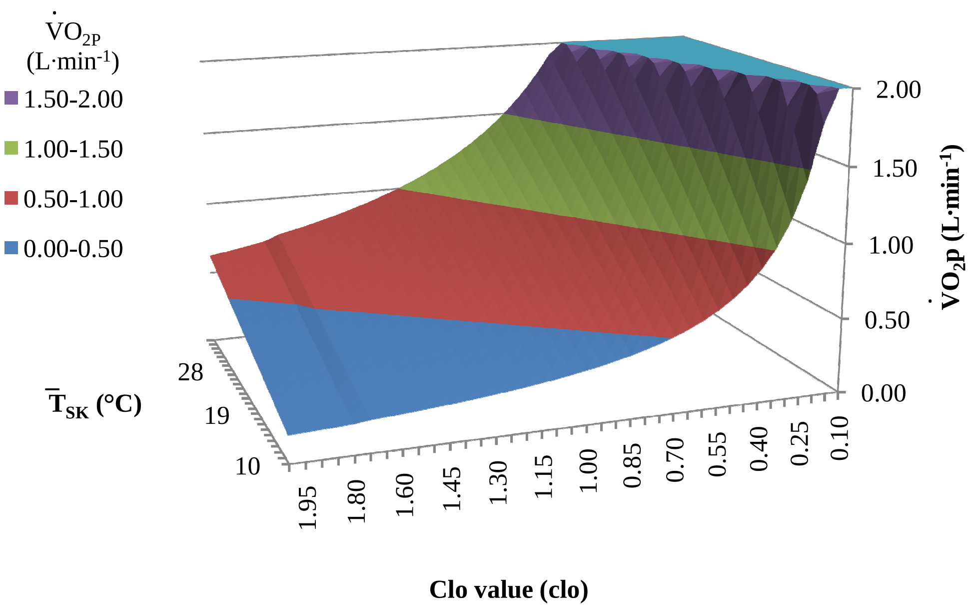

Figure 7.3. Predicted $\dot{V}O_2$ (L·min^{-1}) to remain in thermal balance in 0°C for a 2.0m^2 person for varying $\bar{T}_{SK}$ and clo values .

In an earlier study, Tipton (1991) examined the protection provided by two different helicopter passenger suits, "A" and "B", in 4°C water with 15cm waves. The $\dot{V}O_2$ value of 1.14L·min^{-1} as reported by Tipton, was used as the value associated with maximum shivering capability for individuals in immersion suits in turbulent conditions, since in that earlier previous study the thermoregulatory responses (i.e. shivering) were not able to compensate for the thermal strain and defend against the falling deep body temperature.

Referring to Figure 7.3, we can estimate the amount of heat flow lost to the environment for a given water temperature, $\bar{T}_{SK}$, and clo value when maximally vasoconstricted, and determine if, in theory, the heat flow is compensable by the thermoregulatory system. For example, if a 2.0m^2 person was immersed in a 0.75clo suit in 0°C water and had a $\bar{T}_{SK}$ of 26°C, we would estimate that they would have a $MSHF_P$ of 223.6W·m^{-2}. For this person to remain in thermal balance, that is: produce the same amount of heat being lost to the water, they would have to replace 223.6W·m^{-2} of heat. This would require them to have a $\dot{V}O_{2\ P}$ of 1.23L·min^{-1} to generate

$223.6 W \cdot m^{-2}$ of heat. (Figure 7.4). The $\dot{V}O_{2\ P}$ of $1.23 L \cdot min^{-1}$ is in excess of the $1.14 L \cdot min^{-1}$ reported by Tipton. In this example, the thermal stress would be uncompensable and more heat would flow to the external environment than could be replaced by shivering. In order for the thermal strain to become compensable in this example, the clo value would have to increase to 0.85; this should reduce the amount of heat flow to a level where it can be replaced by shivering at a very high intensity (Figure 7.4).

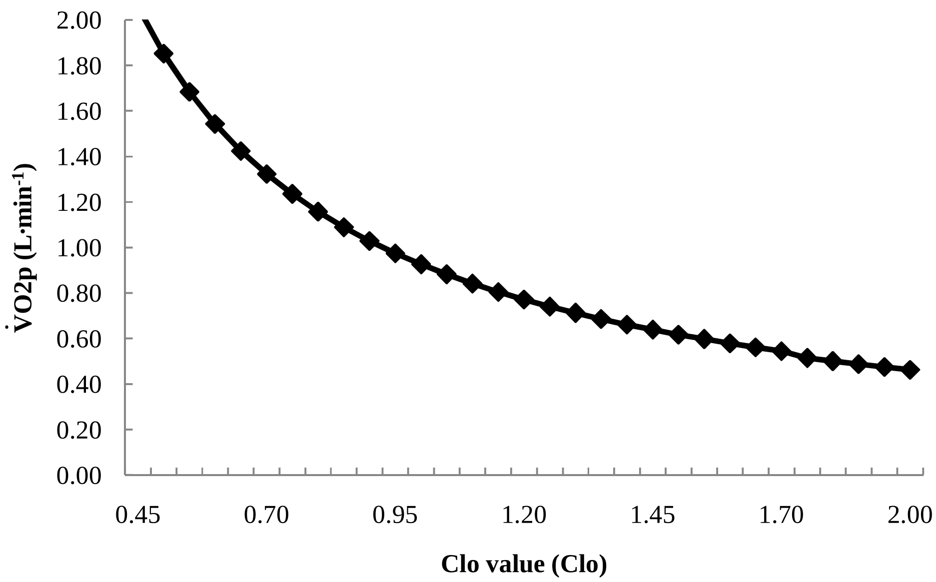

Figure 7.4. $\dot{V}O_{2\ P}$ for a given clo value to remain in thermal balance in 0°C water with a $\overline{T}_{SK}$ of 26°C.

Current IMO Life Saving Appliances (LSA) regulations require that the thermal protective properties of immersion suits prevent a 2°C fall in deep body temperature in 0-2°C calm, circulating water during a 6 hour immersion (IMO, 2010). If the test participants (~ SA of $2.0 m^2$) wore an insulated immersion dry suit with an immersed clo value of 0.80, the data in Figure 7.3 suggests that a $\dot{V}O_{2\ P}$ of $1.02 \cdot min^{-1}$ (in 2°C water) would be required to remain in thermal balance with a $\overline{T}_{SK}$ of 25°C. In the conditions of the present theoretical test we would expect the insulated immersion suit to "pass", since the participant would be able to remain in thermal balance with a moderate to near maximum amount of shivering.

Referring to Figure 7.2, we can expect that when moving to an environment with wind and waves where the immersion suit would experience a drop in clo value of 27%. This would change the immersed clo value from 0.80 to 0.58. With this new clo value, we calculated a $\dot{V}O_{2\ P}$ of $1.48 L \cdot min^{-1}$ would be required to remain in thermal balance (with a $\overline{T}_{SK}$ of 28°C). Since this $\dot{V}O_2$ is greater than the assumed maximum shivering value of $1.14 L \cdot min^{-1}$, the average human would not be able to match the heat lost to the environment and would enter heat debt and consequently become hypothermic. It is not until $\overline{T}_{SK}$ drops to 19°C that the person would be able, theoretically, match the heat flow to the environment through maximum shivering. The drop of $\overline{T}_{SK}$ to a lower value would create a larger thermal gradient within the body.

It was assumed in the previous example that the immersion suit was completely dry before being tested. IMO LSA regulations require that insulated immersions suits go through a jump test to calculate water ingress before testing their thermal protective properties. The IMO LSA states that the jump test would be of sufficient height to fully immerse the body, and no more than 500g of water should leak into the suit (IMO, 2010). In addition to the jump test, a swim test in calm circulating water is conducted and the suit should not take on more than 200g of water (IMO, 2010). Work by The CORD Group Ltd. has suggested that these prescribed jump and swim tests in calm water will significantly underestimate (by as much as 100% for some face-sealed suits) the amount of water that could leak into an immersion suit compared to immersions in wind and waves. (CORD, 2009). If current IMO LSA test standards do not provide rigorous enough test conditions to challenge the water tight integrity of the immersion suits, and significantly underestimate the amount of water that may leak in, suits that were completely dry during those tests may indeed allow water leakage in more realistic conditions.

The addition of as little as 500mL of water underneath the immersion suit will result in a reduction of clo value of 24% in calm circulating water (Figure 7.2). If an immersion suit completes the IMO LSA regulations for both leakage and thermal tests, and has a calculated clo value of 0.80, it may experience a decrease in thermal insulation when moving to rough sea and weather conditions. Firstly, the addition of waves and wind driven spray will challenge the water tight integrity of the immersion suit more than the amount accounted for by the IMO LSA calm water tests. Data from Study 3 show that the addition of water will increase heat flow from the human participants. Secondly, wind and waves will reduce the clo value, leading to an increase in heat flow to the environment. Water leakage into the immersion suit, and immersion in wind and waves, would result in a reduction in clo value of 43% (Figure 7.2). This would cause an immersion dry suit with an immersed clo value of 0.80 (in calm circulating water) to be reduced to 0.46 as a result of water leakage and wind and waves. In 0°C water with a clo value of 0.46, a $\overline{T}_{SK}$ of 28°C, the $\dot{V}O_2$ required by a person of $2.0m^2$ body surface area to remain in thermal balance would be $2.22L \cdot min^{-1}$ (Figure 7.3); a value well in excess of the previously measured, and assumed, average maximal shivering $\dot{V}O_2$ of $1.14L \cdot min^{-1}$ in similar conditions (Tipton, 1991). In this specific scenario, the $\overline{T}_{SK}$ of a person shivering at their maximum ability would have to be at 14°C before thermal balance could be achieved.

The reduction in clo values in more realistic conditions (wind, waves, water leakage) compared to those measured in calm water highlight how the performance of immersion suits can be over-estimated. In calm, benign conditions, the immersed clo value of an immersion suit may allow individuals to thermoregulate successfully in 0°C water, but at a high level of physiological strain on the thermoregulatory system. The pass/fail criterion for the thermal protective properties of immersion suits overlooks the physiological cost required to ensure that deep body temperature does not drop more than 2°C. Moving to more challenging conditions will result in increased strain on the thermoregulatory system of the participants. If the participants were near their maximum ability to thermoregulate in calm, benign conditions, more challenging conditions will increase the thermal stress, resulting in an increase in heat flow to the external environment that may not be able to be compensated by the thermoregulatory system. This uncompensable increase in heat loss will result in the development of hypothermia. Focusing solely on whether or not hypothermia was developed in calm water tests, and not the effort required to pass the test, increases the chances of seeing “surprisingly poor performance” of immersion suits during a maritime accident in more realistic conditions (Tipton, 1995) that push individuals past their thermoregulatory capability to remain in thermal balance.

Chapter 8 – Summary, Correction Factors For Calm Water Tests, and Conclusions

8.1 Summary.

The results from the three studies described in this thesis show that wind and waves will increase MSHF compared to immersions in calm water. While this increase in MSHF was statistically significant, it did not result in a significant change in deep body temperature (Studies 1-3), or metabolic rate (Studies 2 and 3).

Study 1 established that an immersion condition consisting of both wind and waves would significantly increase MSHF compared to calm water, wind-only immersions, and immersions with just waves. Even though MSHF increased by 37% when moving from calm water to immersions with wind and waves, this increase did not result in a significant change in deep body temperature. Given the short immersion duration of only one hour, temperature of the water, and high clo value of the immersion suit, it is not surprising that no change in deep body temperature was measured since the conductive cooling pathway takes an extended period of time to become established and the thermal stress was compensable.

Similar to the findings of Study 1, the results from Study 2 showed that three hour immersions in conditions with wind and waves would significantly increase MSHF compared to calm water. An interesting finding in Study 2 was that there was no significant difference in MSHF between two conditions where one had faster wind speeds and larger wave heights than the other. This suggests that immersion conditions do not have to be extremely turbulent to produce increases in MSHF similar to that seen in rougher conditions. As observed in Study 1, this increase in MSHF did not result in a significant change in deep body temperature during Study 2. Moreover, there were no significant differences in the metabolic rate of the participants across all immersion conditions. Even with the increased immersion durations, the participants were able to compensate for the thermal stress and prevent a change in deep body temperature.

Building upon the findings of Studies 1 and 2, Study 3 examined the effect that 500mL of water underneath the immersion suit had on human thermoregulatory responses in the same conditions as those in the second study. Like the previous two studies, immersions in wind and waves resulted in a significantly greater MSHF compared to calm water. Even with 500mL of water underneath the immersion suit there was no significant difference in MSHF between the two weather conditions, similar to the results seen in Study 2. This suggests that even when wet underneath the immersion suit, tests can be conducted in smaller wind and wave conditions and still obtain levels of heat flow seen in more extreme conditions. There were no significant differences in the change in deep body temperature and metabolic rate across all immersion conditions in Study 3. A summary of the findings from all three studies is given in Table 8.1.

Table 8.1. Summary of findings from Studies 1-3 (Mean [SD]).

	Study 1				**Study 2**			**Study 3**		
	Calm	**Wind**	**Waves**	**W+W**	**Calm**	**Weather 1**	**Weather 2**	**Calm**	**Weather 1**	**Weather 2**
Suit Insulation (Clo)	2.1 [0.2]	1.7 [0.3]	1.7 [0.2]	1.4 [0.2]	1.9 [0.1]	1.5 [0.1]	1.4 [0.1]	1.5 [0.2]	1.2 [0.1]	1.1 [0.1]
MSHF ($W\cdot m^{-2}$)	67.21 [4.7]	79.60 [6.7]	78.80 [4.5]	92.00 [8.39]	62.96 [2.98]	76.75 [6.26]	79.53 [6.24]	79.45 [9.19]	102.06 [11.98]	107.48 [3.63]
$\dot{V}O_2$ ($L\cdot min^{-1}$)	N/A	N/A	N/A	N/A	0.325 [0.054]	0.332 [0.108]	0.365 [0.080]	0.485 [0.096]	0.514 [0.053]	0.526 [0.120]
$\Delta\bar{T}_{SK}$ (°C)	-1.58 [0.62]	-2.49 [0.42]	-2.62 [0.60]	-3.49 [0.44]	-3.39 [0.39]	-4.36 [0.74]	-5.09 [0.79]	-4.27 [0.63]	-5.14 [1.11]	-5.78 [0.61]
ΔT_{GI} (°C)	-0.13 [0.33]	-0.14 [0.25]	-0.03 [0.29]	-0.08 [0.27]	-0.10 [0.31]	-0.29 [0.30]	-0.20 [0.28]	-0.35 [0.14]	-0.38 [0.15]	-0.29 [0.25]

The results from Studies 2 and 3 were used to calculate predicted survival times using the CESM, these were presented in Chapter 7 (Figure 7.1). The CESM predicts that immersions in conditions with wind and waves will reduce survival times, with this reduction becoming smaller the lower the water temperature becomes. The lowest predicted survival times (6.7 h) generated by the CESM were when individuals were immersed in 0°C water with wind and waves, and 500mL of water was underneath the immersion suit.

Figures 7.2 and 7.3 showed, respectively, the changes in clo value due to environmental conditions and the predicted shivering $\dot{V}O_2$ necessary to remain in thermal balance. As immersion conditions reduce the total insulation provided by the immersion suit system (Figure 7.2), the level of physiological cost (metabolic) required to remain in thermal balance increases

(Figure 7.3). When individuals wearing immersion suits are tested in calm water conditions they may be able to remain in thermal balance and prevent hypothermia, but at great physiological cost (i.e. high metabolic rate). However, when moving to more turbulent conditions total system insulation is reduced creating greater strain on the thermoregulatory system to remain in thermal balance. As a result, if the loss of heat to the environment becomes uncompensable hypothermia will result.

8.2 Correction Factors for Calm Water Tests.

The results from the three studies in this thesis show that immersion in wind and waves will significantly increase MSHF compared to calm water. If this increase in heat flow cannot be compensated for by the thermoregulatory system, hypothermia will develop. Therefore it is important to test immersion suits in conditions representative of those found offshore in order to ensure that they perform as expected.

However, it may not always be possible to test in these conditions for financial and practical reasons. There are very few facilities in the world with wave tanks capable of generating conditions representative of those offshore. A more practical solution may be to develop corrections factors for testing immersion suits in calm water, as suggested by Tipton (1995). By factoring in the reduction in total insulation caused by wind and waves, it may be possible to test immersion suits in calm water conditions and still achieve an acceptable level of performance in conditions that have wind and waves. Using the data presented in Figures 7.2 and 7.3, these correction factors were developed. [8]

A value of $0.72\text{L}\cdot\text{min}^{-1}$ was chosen for $\dot{V}O_2$ based on earlier work by Tipton (1991) in which participants performed immersions in 4°C water with 15cm waves in two different suits: A and B. The $\dot{V}O_2$ values associated with the uncompensable heat loss in suit A ($1.14\text{L}\cdot\text{min}^{-1}$) was used earlier in section 7.3: "$\dot{V}O_{2\ P}$ Required to Maintain Thermal Balance", as the maximum shivering intensity. In the same study, Tipton reported a $\dot{V}O_2$ of $0.72\text{L}\cdot\text{min}^{-1}$ when the participants wore

[8] Refer to sections 3.5.6-3.5.8 for the equations.

suit B and were able to stabilize their deep body temperature (Tipton, 1991). The $\dot{V}O_2$ value of $0.72L{\cdot}min^{-1}$ is less than that associated with maximum shivering ($1.14L{\cdot}min^{-1}$), but at a sufficient level to maintain deep body temperature. As a result, a $\dot{V}O_2$ of $0.72L{\cdot}min^{-1}$ was chosen as a value that allows for shivering to be at a moderate rate, but not near a maximum, while still maintaining a stable deep body temperature.

This gives $\dot{M}$ a value of $130.43W{\cdot}m^{-2}$; a level of heat production associated with maintaining a stable deep body temperature in challenging immersion conditions (Tipton 1991). Theoretically, to remain in thermal balance at this moderate level of shivering, the level of heat flow should not exceed $130.43W{\cdot}m^{-2}$. If we assign a value of $130.43W{\cdot}m^{-2}$ to the predicted MSHF ($MSHF_P$) we can calculate a clo value at a given water temperature and $\bar{T}_{SK}$ to equal that level of heat flow[9].

A $\bar{T}_{SK}$ of 27°C was chosen as in the previous study by Tipton (1991), when wearing the suit that gave the $\dot{V}O_2$ value of $0.72L{\cdot}min^{-1}$, $\bar{T}_{SK}$ fell to 29°C after 45 minutes of immersion, but continued to drop. The average $\bar{T}_{SK}$ values were not reported after 45 minutes, but the $\bar{T}_{SK}$ of one participant was, and it was 24°C after 6 hours. For the correction factors, 27°C was chosen for $\bar{T}_{SK}$ since it is mid way between the average $\bar{T}_{SK}$ reported at 45 minutes for the group, and 24°C at 6 hours for one participant.

With a $MSHF_P$ of $130.43W{\cdot}m^{-2}$, and a $\bar{T}_{SK}$ of 27°C, a clo value for a given water temperature can be calculated. For example, in 0°C water, a clo value of 1.34 would be required to ensure a maximum heat flow of $130.43W{\cdot}m^{-2}$ with a $\bar{T}_{SK}$ of 27°C. The clo value of 1.34 can be considered the “minimum” clo value required to ensure $\dot{V}O_2$ does not increase above $0.72L{\cdot}min^{-1}$, and that the physiological strain to thermoregulate is only moderate.

Figure 7.2 provides the reduction in clo value due to leakage and wind and waves. Leakage (500mL of water) under the immersion suit will reduce clo values by 24%; to account for this reduction the minimum clo value of 1.34 should be increased to 1.76 in order to ensure heat flow of $130.43W{\cdot}m^{-2}$ in 0°C water. Wind and waves will reduce clo values by 27%; the minimum clo

[9] Refer to section 3.5.8 for the equations.

value of 1.34 should be increased to 1.83clo to account for this. Wind, waves, and leakage will reduce clo values by 43%; the minimum clo value of 1.34 should be increased to 2.34 to account for those factors.

The equations to calculate the minimum clo, and correction factors for leakage, wind and waves are:

Minimum (Calm Water):
$Clo = 1.335 – 0.049 \cdot T_W$

500mL of Water:
$Clo = 1.734 – 0.064 \cdot T_W$

WW (Wind and Waves):
$Clo = 1.829 – 0.067 \cdot T_W$

WW + 500mL of Water:
$Clo = 2.343 – 0.086 \cdot T_W$

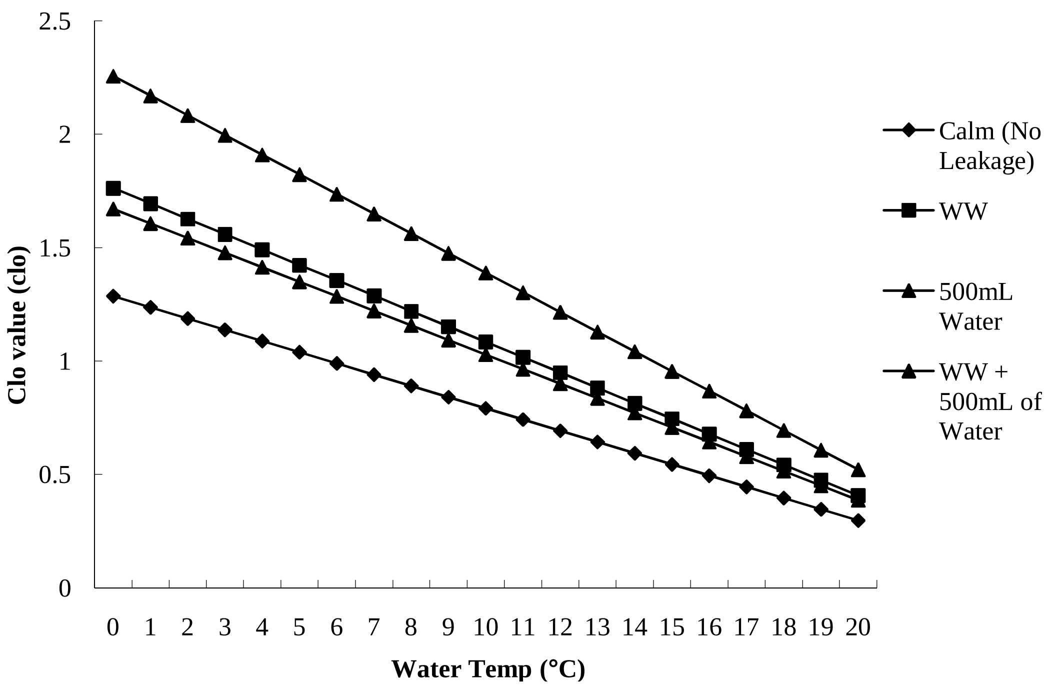

Figure 8.1. Predicted clo value to remain in thermal balance for a given water temperature for a $2.0m^2$ individual with a $\overline{T}_{SK}$ of 27°C, and a $\dot{V}O_2$ of $0.72 L \cdot min^{-1}$ (WW = wind and waves).

In theory, these correction factors can be used to determine what clo value an immersion suit should have during a calm water test, for a given area of operation in order for a person to remain in thermal balance with moderate thermoregulatory effort. For example, if an offshore oil operator wanted to select an immersion suit for their installation that was located in an area that had a mean water temperature of 7°C with calm seas, then they could choose the "Calm – No Leakage" equation to calculate a clo value an immersion suit should achieve in calm water tests (0.9clo). If they wished to account for leakage, then they could use the "500mL of Water" calculation to determine a clo value an immersion suit should achieve when dry during calm water tests (1.2clo). If the same operator had an installation located in an area that had an average water temperature of 0°C with frequently stormy seas, then they could use (at a minimum) the "WW" equation to determine a clo value to achieve during calm water tests to account for wind and waves (1.8clo), or "WW + 500mL of Water" to account for rough seas and 500mL of leakage (2.3clo).

8.3 Conclusions.

It is concluded that immersions in wind and waves will significantly increase MSHF compared to calm water immersions. If this increase in heat flow cannot be compensated for by the thermoregulatory system, a drop in deep body temperature may occur that was not observed during more benign tests. Therefore, it is recommended that when measuring the performance of immersion suits, tests should be conducted in conditions that are as representative of the range of conditions which are expected in the operational area for the immersion suit. If it is not possible to conduct tests in these conditions due to financial or logistical constraints, then it is recommended that the equations described in section 8.2 be considered, and validated, to add a correction factor for the reduction in clo value when moving from calm water to rougher conditions that include wind, waves, and leakage. The use of these correction factors would have important benefits for marine safety, as they would help ensure an expected level of performance of people and immersion suits in wind and waves even in the absence of facilities capable of creating such rough conditions. Accurate performance could be assessed in a setup as simple as a chilled water bath capable of fully immersing an individual wearing an immersion suit.

Chapter 9 – Assumptions, Limitations and Delimitations

Several assumptions, limitations and delimitations were associated with the studies described in this thesis.

9.1 Assumptions.

For all studies, before each test session, all participants were asked to refrain from consuming alcohol the night before, caffeine 3-4 hours before, and eat a balanced meal 2-5 hours beforehand. It was assumed that participants complied with these instructions and were in the same physiological state for each test.

When calculating MSHF, the sum of all 12 weighted heat flow measurement sites were divided by 0.95 to account for the lack of a hand measurement. This method assigns a value of 5% of the total MSHF calculated from the other 12 measurement sites to the hand. Due to vasoconstriction, the amount of heat flow from the hand will be significantly reduced as the body begins to cool. Assuming that the hand will contribute 5% of the total MSHF may overestimate the amount of heat lost from that location.

For all three studies, it was assumed that administering the gastro-intestinal temperature pill 40 minutes prior to starting a test would be a sufficient amount of time for it to be consistently place within the gastro-intestinal tract. While the pill manufacturer (HQ Inc. Palmetto, Florida, USA) recommended a two-hour period between ingestion and monitoring of it, they indicated that this was to ensure that drinking fluids would not affect the measurements from the pill. Given that our participants did not consume any fluids after ingesting the pill, it was assumed that the 40 minute period would be sufficient. It was also assumed that if pill was still present in the participant from an earlier test, it could be used again. Recent work by Domitrovich and colleagues has shown that there were no significant differences in T_{GI} measurements between two pills (one ingested 24 hours prior, the second 40 minutes prior) during strenuous exercise (Domitrovich et al., 2010).

9.2 Limitations.

The Offshore Engineering Basin (OEB) at NRC-IOT does not have the ability to control the temperature of the air and water. This resulted in water and air temperatures much higher than those found in conditions offshore (Chapter 1 – Table 1.1). Additionally, the water in the OEB would continue to rise during each study. The OEB was periodically drained and refilled with water from the local municipal source in an effort to maintain a stable temperature. This resulted in some difference in water temperature for each test condition, but it was not statistically significant. Across all conditions, the water temperature ranged from 9.78 – 12.16°C in Study 1; 10.19 – 11.50°C in Study 2; and 5.94- 9.33°C in Study 3.

The OEB is capable of generating waves up to a maximum height of 0.9m, and wave heights offshore can be up to 4-5 times larger than this (Chapter 1 – Table 1.1). The wave spectra used during each test program were truncated thereby excluding spectrums that contain larger wave heights. Relative to the size of these larger wave heights and lengths, the participants would experience these as waves as a swell, and would be the equivalent of a small particle floating on the surface of the water. For this reason, and due to the maximum wave height of 0.9m capable of being generated, the wave spectrums used in the studies were truncated from those seen offshore. Even though the waves were smaller in height than those found offshore, the amount of MSHF may have been the same. Witherspoon and colleagues found that convective heat flow reached a maximum value even as water velocity increased (Witherspoon et al., 1971). It is therefore likely that the heat flow seen in the wave conditions used in this thesis would have caused the same amount of MSHF as that seen in larger waves offshore.

9.3 Delimitations.

For all three studies, young healthy individuals were chosen as participants in order to reduce the risk of any injuries occurring during the tests from pre-existing health conditions. Consequently, the results reported in this thesis are limited to that particular demographic, and older individuals with pre-existing conditions may have responded differently.

Only two participants who volunteered in Study 1 were female. Due to the equipment used to manage urination in Studies 2 and 3, females were not recruited. The majority of participants tested in the studies were male, and the results reported are limited to that gender.

Only one style of immersion suit was used for all three studies. Consequently, the results from these studies are limited to the responses of participants in one particular brand of immersion suit. It is possible that in other suits, the thermal responses to wind and waves may be different.

Chapter 10 – Recommendations for Future Work

The studies described in this thesis attempted to address the knowledge gap that exists between the performance of individuals in immersion suits in calm water conditions they are often certified in, and in rougher conditions that include both wind and waves. The effect of wind and waves on human thermoregulatory responses were quantified in this thesis, and in the process, several more areas of potential research were identified.

The majority of participants used in this study were young healthy males. Future studies should use females, as well as an older demographic.

While thermal manikins are can be used to certify immersion suits, there exists important segmental differences between them and humans with regards to areas of major heat flow. Future work should attempt to correlate thermal manikin results with those of humans to ensure that immersion suits benefit the latter more than the former.

The brand of immersion suit used in the studies described in this thesis is of very high quality, and has a higher clo value compared to other more popular immersion suits. The increase in MSHF due to wind and waves may be different for another brand of immersion suit. The performance of more popular brands of immersion suits (both marine abandonment and helicopter passenger transportation) in conditions that include wind and waves should be assessed, if not already done so. The immersion suit used in this study was selected because it had latex neck and wrist seals, which prevented water ingress from occurring. This ensured a new variable was not introduced (water leakage) during the tests.

Combined with the high level of insulation provided by the immersion suit used, the water and air temperatures were not low enough to challenge the thermoregulatory system of the participants. Future studies should repeat these tests, but in colder water and air temperatures.

Conducting immersion suit tests in only calm water will overestimate performance compared to testing in wind and waves. However, there are few facilities in the world that have wave pools capable of producing wave heights similar to that seen in the open ocean. It would not be practicable or financially feasible to perform all immersion suit tests in these unique facilities. A potential research project is to replicate the effect of heat loss due to waves in facilities that are not capable of generating them. NRC-IOT has conducted some work investigating the effect of increasing the velocity of the water past the participant on MSHF. It was found that by moving the water past the participant at the same rate as it would travel past due to wave motion, the increase in heat loss due to waves can be replicated in facilities not capable of generating them (Power and Simoes Re, 2011). This method is much more financially feasible, and practical, compared to testing in wave tanks yet still offers the ability to assess performance of individuals and suits in conditions more challenging then calm water.

An even more financially feasible, long term solution would be to validate the equations listed in section 8.2 of this thesis. A future research project could validate if the calm water clo values specified by the equations in section 8.2 to correct for the effect of wind and waves do result in a participant remaining in the thermal balance in the more extreme conditions. If these correction factor equations are experimentally verified, it would allow for the testing of participants and immersion suits in calm water conditions, reducing the need for unique facilities capable of generating wind and waves.

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Appendix A – Survival Time Prediction Reports

Predictions of Survival Time for Individuals Immersed in Water and Wearing a Survival Suit

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Report on survival time estimations for PJ 2264 prepared for Jonathan Power, NRC Institute of Ocean Technology.

Introduction

Search and Rescue is reliant on tools that guide decisions on rescue planning and operations, as for example having an estimation of a casualty's survival status. One such tool is the Cold Exposure Survival Model (CESM), which is designed to predict the survival time (ST) of individuals exposed to cold, whether exposed to air or immersed in water (Tikuisis 1997; Keefe and Tikuisis 2008). This report presents the predictions of the survival status of individuals wearing a White's Marine Abandonment Suit that was used in a series of cold water immersion experiments conducted by Power et al. (2008, 2009).

The first section of this report presents a comparison of measured and predicted values at the end of 3 h of the experimental immersion conditions reported by Power et al. (2009). The second section presents survival time predictions for hypothetical situations in which water leaks into the suits. This will demonstrate the incapacitation of survival suits when degraded by water leakage whether due to accident, poor fit, or poor maintenance. The final section will summarize the findings with recommendations for further inquiry.

Comparison of Measured and Predicted Thermal Status of Experimental Subjects

In brief, the experiment involved 3 hours of head-out immersion of 12 males (mean age 24 yrs, height 1.81 m, weight 83.2 kg, and body fat 16.8%) wearing a survival suit (White's Marine Abandonment Suit with undergarment) in water at about 11°C under both calm and turbulent conditions (Power et al. 2009). The in-situ insulation of the survival suit was measured using a manikin purposely designed for such an evaluation (CORD 2008). Under calm (windless flat water) and turbulent (5.5 m/s wind and 0.67 m waves) conditions, the survival suit's in-situ insulation were 1.098 and 0.796 clo, respectively.

As a survival prediction model, CESM is designed to estimate the time taken for an individual's deep body temperature to reach 28°C, assumed as the point of imminent death due to hypothermia (Keefe and Tikuisis 2008). As such, the vast majority of this cooling time is characterized by either a continuous decline in body temperature or steady state heat balance, depending on the severity of the cold insult. That is, if heat loss is less than the individual's maximum possible heat generation from shivering, then the individual should reach a steady state heat balance with no further decrease in body temperature until shivering fatigue (Tikuisis et al. 2002; Tikuisis 2003). Under this latter condition, which pertains to the experimental situation, the relatively short period of initial net heat loss upon immersion, typically characterized by a transient rise in deep body temperature due to vasoconstriction of the skin, is bypassed in CESM. In practical terms, CESM's prediction just after the start of immersion reflects the thermal response beyond the transient period and therefore will indicate lower body temperatures than actually measured. This is because the 'modelled' body is allowed to cool sufficiently so that the predicted rate of heat loss can be countered by the predicted shivering heat production, which is driven by decreases in both deep body and skin temperatures. The eventual prediction of survival time based on deep body cooling to 28°C is not sensitive to the transient period given the relative shortness of the latter period to the former.

Assuming that the transient period is approximately 1 h for the immersion conditions of the study[*], Table 1 compares the CESM-predicted thermal response values after 2 h of immersion with the measured values of the subjects at the end of their 3 h of immersion. Table 1 also shows the predicted thermal status of the subjects at the end of 36 h of immersion, which is the limit of CESM's predictive range (causes of death other than hypothermia are more likely to occur if individuals survive 36 h of immersion). An additional caveat of CESM is that it does not have an input field for wave height; instead, it only allows for either light or heavy seas. In the present circumstance, 'light' is assumed for the calm condition and 'heavy' is assumed for the turbulent condition (i.e., with wind and waves irrespective of their values provided that the individual experiences significant water movement, which is assumed for both Weather #1 and #2 conditions).

The predicted decreases in body temperatures are much greater than measured, which was not unexpected, as explained above. The predicted metabolic rate is higher than measured, driven by the predicted decreases in body temperatures. Notwithstanding the limitations of CESM, an

[*] Of the subjects whose deep body temperatures initially rose upon immersion (6 and 9 for the calm and high turbulent conditions, respectively), they returned to their starting values after respective mean times of 73 and 62 min of immersion.

additional explanation for these overpredictions is taken up in the Discussion. That the measured heat loss exceeds the measured metabolic rate indicates that the subjects had not attained heat balance at the end of 3 h of imersion, which concurs with the further predicted decreases in body temperatures and increase in metabolic rate predicted after 36 h of simulated immersion.

Table 1. Measured and predicted changes in thermal status for the experimental test conditions. Water temperature was 11°C, and respective wind speed and wave height were 3.5 m/s and 0.34 m for Weather #1, and 4.6 m/s and 0.67 m for Weather #2. Predicted values for the turbulent condition apply to both Weather #1 and #2.

Condition	Change in Deep Body Temperature (°C)			
	Meas ± SD	Pred 2 h	Pred 36 h	
Calm	0.10 ± 0.31	1.03	1.23	
Weather #1	0.29 ± 0.30			
Weather #2	0.20 ± 0.28	1.21	1.45	
	Change in Mean Skin Temperature (°C)			
	Meas ± SD	Pred 2 h	Pred 36 h	
Calm	2.96 ± 0.43	6.39	6.51	
Weather #1	3.46 ± 0.72			
Weather #2	3.95 ± 0.66	8.40	8.53	
	Mean Body Heat Flow and Metabolic Rate (W/m^2)			
	Meas BHF ± SD	Meas MR ± SD	Pred MR 2 h	Pred MR 36 h
Calm	63.0 ± 3.0	55.8 ± 7.6	68.5	82.5
Weather #1	76.8 ± 6.3	57.9 ± 19.0		
Weather #2	79.5 ± 6.2	62.6 ± 11.5	93.9	96.8

Under no condition did CESM predict that the subjects' deep body temperature would reach lethal hypothermia (drop of 9°C) within 36 h of immersion. Indeed, the predicted changes in the subjects' thermal status at the end of this period are not markedly higher than predicted after 2 h of immersion indicating that the subjects were close to attaining steady state heat balance soon after and should not sucumb to hypothermia unless leakage of water compromised their suit's insulation, which is considered in the next section.

Predicted Survival Status of Individuals During Various Hypothetical Immersion Conditions

This section provides estimations of the subjects' survivability if the survival suits that they wore developed a leak. Four levels of wetness are assumed for this demonstration: ingress of 0.1 L/m^2 (equivalent to an even spread of 0.1 mm height of water or a total of 200 mL for a body surface area of 2 m^2) considered damp, 1 L/m^2 considered moderately wet, 5 L/m^2 considered soaked, and nude (for comparative purposes). Figure 1 shows the predicted survival times (up to 36 h) for calm and turbulent (applies to both Weather #1 and #2 conditions) immersions in water from 0 to 20°C. Included in this display are estimations for the survival suit when kept dry.

As indicated earlier, the subjects are predicted to survive at least 36 h of immersion while wearing the dry survival suit in the experimental water temperature of around 11°C. Note, however, that the survival time reaches the 36 h prediction limit in water less than 2°C under calm conditions and less than 8°C in turbulent water. In the extreme case of dry suit immersion in 0°C turbulent water, the predicted survival time diminishes to less than 16 h.

Further decreases in survival time are apparent with water leakage into the survival suit, as evident in Fig.1. Survival time is seen to diminish markedly under the damp condition, cutting almost a third of the time compared to the dry condition. Increasing wetness further also demonstrates a disproportionate decrease in survival time. For example, increasing wetness by an order or magnitude (10x) from the damp to wet condition diminishes survival time by roughly another third. Finally, a completely soaked survival suit will afford better protection than if the subject was nude, but the advantage dissipates quickly as water temperature decreases.

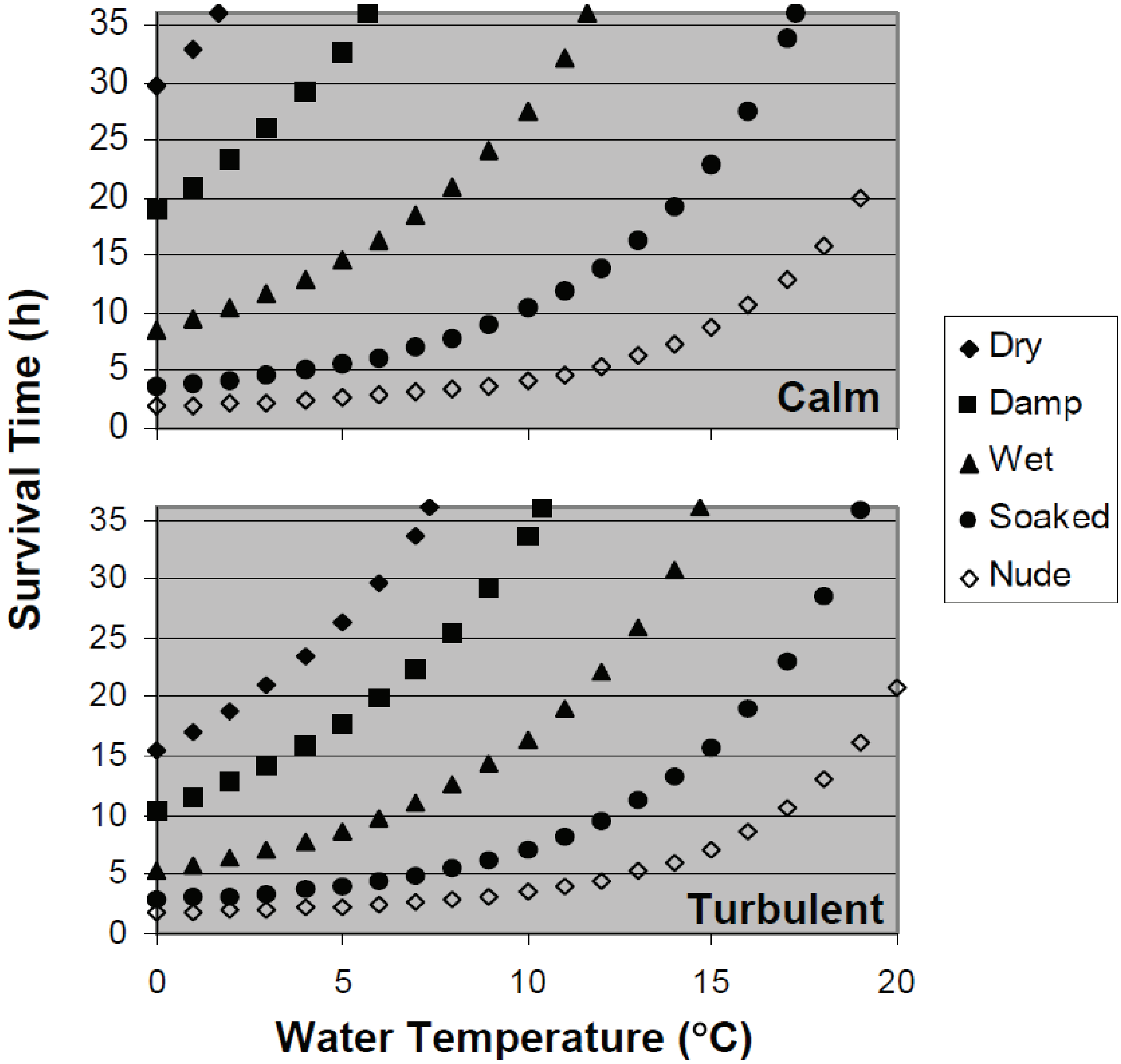

Figure 1. Survival time predictions for calm and turbulent water immersions for the subjects wearing the survival suit under dry and various wetness conditions, in addition to a nude condition.

It is also instructive to consider the range of survival times as individual body sizes/shapes vary. The predicted survival times for the leanest and largest subjects of the study based on body fatness are shown in Fig. 2 for immersion in turbulent water under dry and wet survival suit conditions. When the survival time is less than 36 h for both subjects, the largest subject is predicted to survive at least twice as long as the leanest subject.

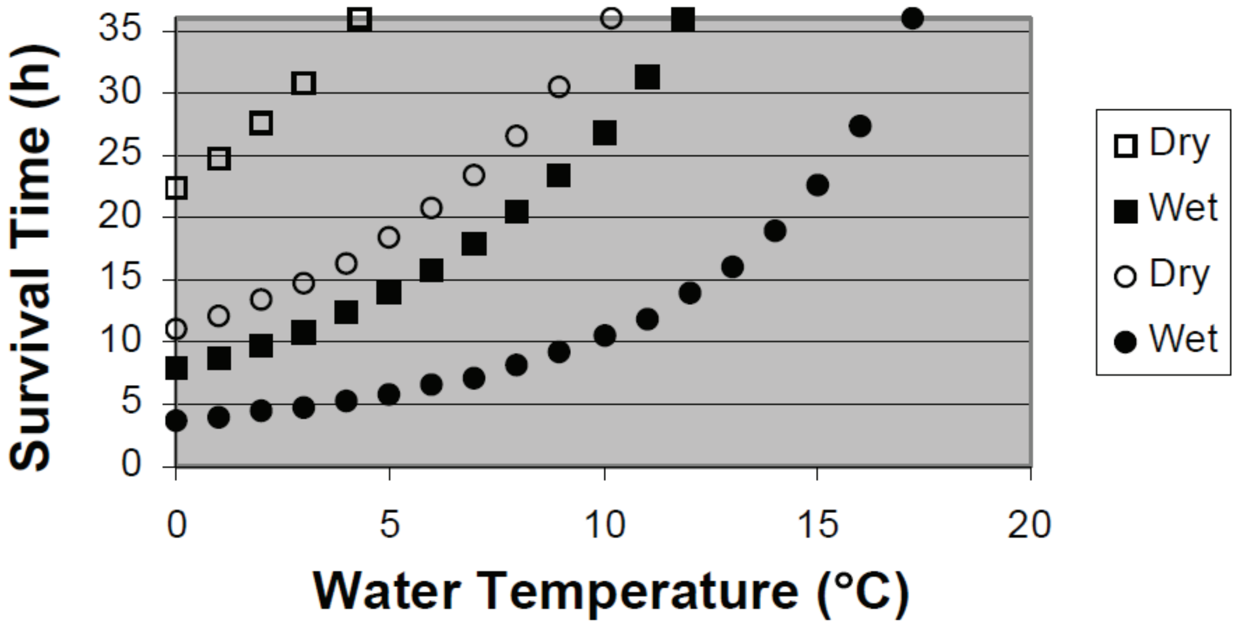

Figure 2. Comparison of predicted survival times for the leanest (○●; 1.77 m, 68 kg, 10.3% body fat) and largest (□■; 1.75 m, 95 kg, 24.4% body fat) subjects immersed in turbulent water under dry and wet survival suit conditions.

Discussion and Recommendations

Although CESM is not designed to predict the early response of individuals immersed in cold water, comparison with the measured values nevertheless suggests that the decreases in body temperatures and increase in metabolic rate are over predicted. This disparity might be partially explained by the possibility of varying survival suit insulation. Given that the insulation of the survival suit is based on a steady state condition measured on a manikin from 75 min to 4 h after the start of immersion (CORD 2008), it is conceivable that the suit's insulation is initially higher due to the time taken for the suit to fully adjust to the environmental condition (e.g., with further compression of clothing insulation). If so, then a resultant higher initial insulation would impose a lesser cold insult to the body leading to a slower initial decline in body temperatures and consequent lower metabolic rate than predicted by assuming the steady state value of insulation.

The most striking finding in this report is the marked decrease in survival time if the survival suit is compromised by water leakage, even a modest amount. Similar to wind chill where the initial increment in air movement has a disproportionally high impact on surface cooling, the initial increment of water leakage causes significant degradation in suit insulation. It is noteworthy that even if a survival suit did not leak, sweating due to high exertional effort would degrade suit insulation. Hence, future studies should consider trials with wetted suits, whether on humans or manikins, to fully appreciate the consequences of leakage for educational/instructive and contingency design purposes. Also reinforced in this report is the vast difference in survival times between low and high fat individuals. To promote the survivability of the former, consideration should also be given to over-sizing their suits to allow for extra clothing/ undergarments that would provide additional protective insulation.

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Predictions of Survival Time for Individuals Immersed in Water and Wearing a Wetted Survival Suit: Phase 2

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Report on survival time estimations for Phase 2 of Contract No. 743545 prepared for Jonathan Power, NRC Institute of Ocean Technology.

Introduction

This report presents the predictions of the survival status of individuals wearing a wetted White's Marine Abandonment Suit that was used in a cold water immersion experiment conducted by Power et al. (2010). It follows the earlier Phase 1 report (Tikuisis 2010) on the survival status of similar individuals wearing the same suit, but under a dry condition. The reader is referred to the Phase 1 report for an introduction to the Cold Exposure Survival Model (CESM; Tikuisis 1997; Keefe and Tikuisis 2008) used for survival time predictions including underlining assumptions and caveats regarding its use.

The first section of this report compares measured and predicted values of the subjects' thermal status at the end of the 3 h experimental immersion study conducted by Power et al. (2010). The second section presents survival time predictions for various other degrees of wetness including a dry condition. This will demonstrate the incapacitation of survival suits when degraded by water leakage whether due to accident, poor fit, or poor maintenance. The third section compares the survival predictions for the leanest and largest individuals of the study, which will re-emphasize the natural insulative benefit of high body fatness under conditions of cold exposure. The final section will summarize the findings.

Comparison of Measured and Predicted Thermal Status of Experimental Subjects

The experiment involved 3 hours of head-out immersion of 12 males (mean age 26 yrs, height 1.81 m, weight 82.7 kg, and body fat 18.8%) wearing a survival suit (White's Marine Abandonment Suit with undergarment) in water of about 8.5°C under both calm and turbulent conditions (Power et al. 2010). The in-situ insulation of the dry survival suit was measured using a manikin purposely designed for such an evaluation (CORD 2008). Under calm (windless flat water) and turbulent (5.5 m/s wind and 0.67 m waves) conditions, the survival suit's in-situ dry insulation (including undergarment) were 1.098 and 0.796 clo, respectively. In the current experiment, subjects were wetted by having 250 mL of water applied to each side of their torso while wearing the undergarment for a total wetness of 500 mL. Using an estimation of the degradation of insulation dervived from the data of Allan et al. (1985), the resultant in-situ insulation of the survival suit is estimated to decrease to 61% of its dry value when wetted by this amount of water (implicit is the uniform transfer of some wetness from the undergarment to the suit once the subject is fully encapsulated). Thus, the in-situ wetted survival suit's ensemble insulation values assumed in this study were 0.670 and 0.486 clo under the calm and turbulent conditions, respectively.

CESM (Cold Exposure Survival Model) is designed to predict the time taken for an individual's deep body temperature to reach 28°C, assumed as the point of imminent death due to hypothermia (Keefe and Tikuisis 2008). Given that the vast majority of cooling time is characterized by either a continuous decline in body temperature or steady state heat balance depending on the severity of the cold exposure, the model bypasses the relatively short initial transient adjustment of deep body temperature upon immersion. Hence, CESM's prediction immediately after the start of immersion reflects the thermal response beyond the transient period and consequently will indicate lower body temperatures and higher metabolic rates than actually measured.

Deep body temperatures initially rose upon immersion in about half of the subjects and these temperatures returned to their starting values in average times of about 81 and 105 min under the calm and turbulent conditions, respectively. As an approximation, therefore, the measured thermal responses with a lead of 1.5 h were compared to the predicted responses. That is, Table 1 compares the CESM-predicted thermal response values after 1.5 h of immersion with the measured values of the subjects at the end of their 3 h of immersion. No distinction was made for the two 'Weather' conditions (i.e., wind speeds and wave heights of 3.5 m/s and 0.34 m for Weather #1, and 4.6 m/s and 0.67 m for Weather #2) since the dry survival suit's insulation was measured under one turbulent condition and CESM does not have an input field for wave height. Instead, it only allows for either light or heavy seas, which in the present circumstance is assumed for the calm and turbulent conditions, respectively.

The predicted decreases in body temperatures are much greater than measured, which was expected, as explained above. The predicted metabolic rate is also higher than measured, driven by the predicted decreases in body temperatures. Additional explanations for these overpredictions are discussed in the Phase 1 report (Tikuisis 2010) and in the summary of this report. The measured heat losses exceed the measured metabolic rate for the turbulent condition and suggest that the subjects had not attained heat balance at the end of 3 h of imersion, which concurs with further predicted decreases in body temperatures and increase in metabolic rate predicted beyond 3 h of simulated immersion. Under all test conditions, CESM predicted that the subjects' deep body temperature would reach lethal hypothermia (drop of 9°C from 37°C) within 36 h of immersion.

Table 1. Measured and predicted changes in thermal status for the experimental test conditions. Water temperature was approximately 8.5°C, and respective wind speed and wave height were 3.5 m/s and 0.34 m for Weather #1, and 4.6 m/s and 0.67 m for Weather #2. Predicted values for the turbulent condition apply to both Weather #1 and #2.

Condition	Decreases in			
	Deep Body Temperature (°C)		Mean Skin Temperature (°C)	
	Meas ± SD	Pred 1.5 h	Meas ± SD	Pred 1.5 h
Calm	0.37 ± 0.28	1.22	2.76 ± 0.73	10.96
Weather #1	0.27 ± 0.26		3.20 ± 0.92	
Weather #2	0.28 ± 0.23	1.23	3.61 ± 0.65	13.07
	Mean Body Heat Flow and Metabolic Rate (W/m^2)			
	Meas BHF ± SD	Meas MR ± SD	Pred MR 1.5 h	
Calm	81.2 ± 9.3	83.1 ± 10.7	112.7	
Weather #1	103.3 ± 11.2	88.8 ± 7.6		
Weather #2	107.5 ± 3.6	93.0 ± 19.6	135.8	

Predicted Survival Status of Subjects During Various Immersion Conditions

This section provides estimations of the subjects' survivability under various levels of wetness including the experimental, dry, and nude conditions. Specifically, five levels are considered:

dry, wetnesses of 0.1 L/m^2 (equivalent to an even spread of 0.1 mm height of water or a total of 200 mL for a body surface area of 2 m^2) considered damp, 0.25 L/m^2, which represents the experimental '500 mL' condition, 5 L/m^2 considered soaked, and nude (for comparative purposes). Figure 1 shows the predicted survival times (up to 36 h) for calm and turbulent (applies to both Weather #1 and #2 conditions) immersions in water from 0 to 20°C.

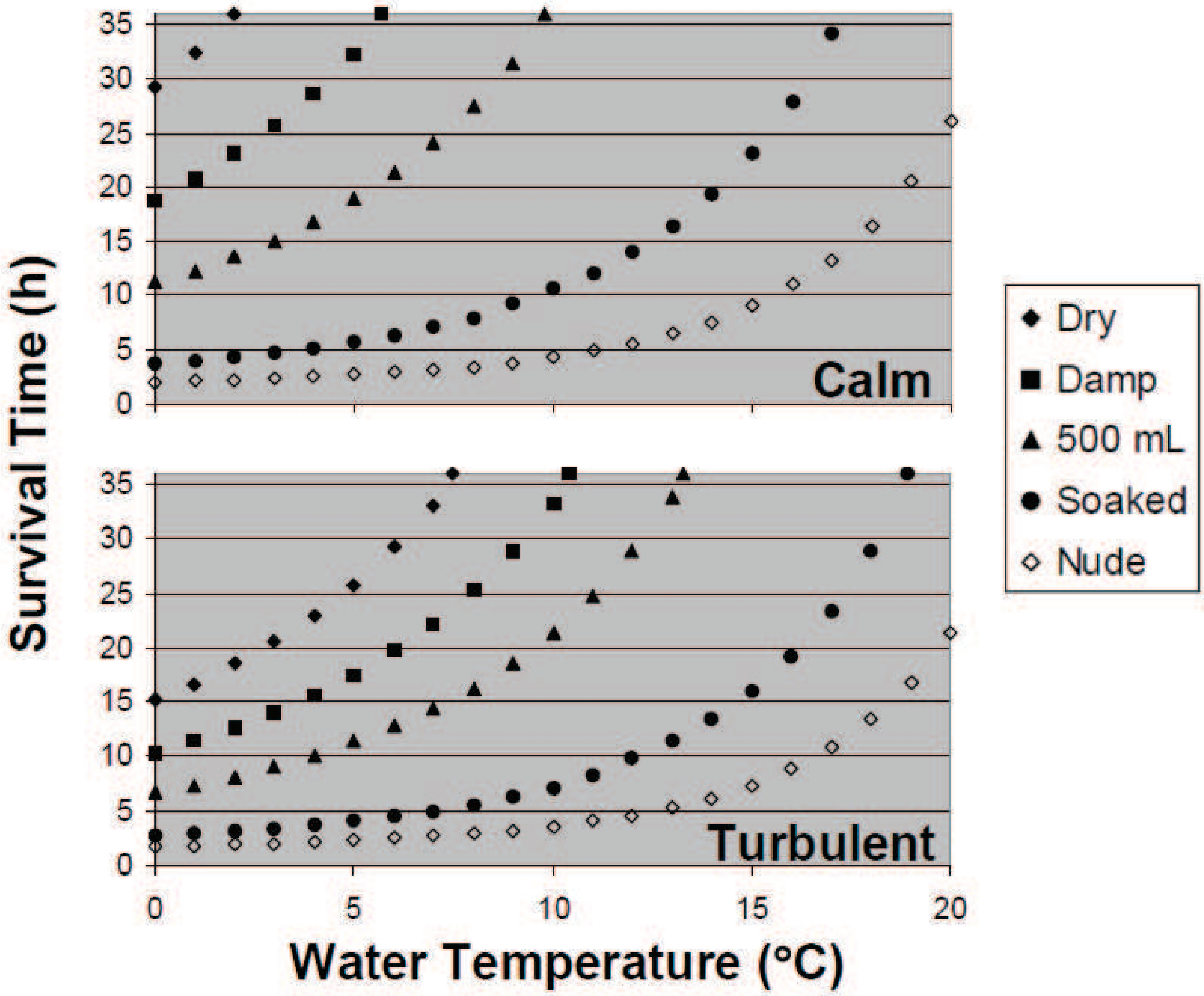

Figure 1. Survival time predictions for calm and turbulent water immersions for the average subject wearing the survival suit under dry and various wetness conditions, in addition to a nude condition.

As indicated earlier, the subjects are not predicted to survive 36 h of immersion while immersed with the wetted survival suit in the experimental water condition of about 8.5°C. However, if the suit was dry, the survival time reaches the 36 h prediction limit in water less than 2°C under calm conditions and less than 8°C in turbulent water. Further, the 36 h limit is reached under various levels of wetness at higher water immersion temperatures, except for the nude condition in which case the predicted survival time for the average subject is less than 36 h, even in water at 20°C. The marginally higher predicted survival times compared to Fig. 1 in the Phase 1 report (Tikuisis 2010) is attributed to the slightly higher average body fatness of the subjects in the current study. The observation of a disproportionate decrease in survival time with increasing wetness reported in the Phase 1 report is replicated here, noting in particular that the application of 500 mL of water to the subjects' clothing degraded the survival suit's insulation to 61% of its dry value leading to diminished survival times by 38 and 44% compared to a dry condition under calm and turbulent water, respectively.

Predicted Survival Status of the Leanest and Largest Subjects During Various Immersion Conditions

As in the Phase 1 report, consideration is given to the range of survival times for varying individual body sizes/shapes. This was done by comparing the predicted survival times for the leanest and largest subjects of this study based on body fatness, as shown in Fig. 2 for immersions in both calm and turbulent water under dry and wetted survival suit conditions. When the survival time is less than 36 h for both subjects, the largest subject is predicted to survive about 50% longer than the leanest subject.

In order for the leanest subject to survive as long as the largest subject under the same environmental conditions, additional insulation is required. This increase can be calculated by increasing the in-situ clo value until the predicted survival time of the leanest subject matches that of the largest subject without any adjustment of the latter's insulation value. Interestingly, the additional insulation varies according to the environmental condition. Under the calm water condition, the leanest subject requires approximately 13 and 21% additional 'in-situ' insulation to survive as long as the largest subject for the dry and wetted (500 mL) conditions, respectively. Under the turbulent water condition, the required increases are 17 and 30% for the dry and wetted conditions, respectively. These estimates indicate that wetness increases the required additional insulation by about another two-thirds compared to the dry condition.

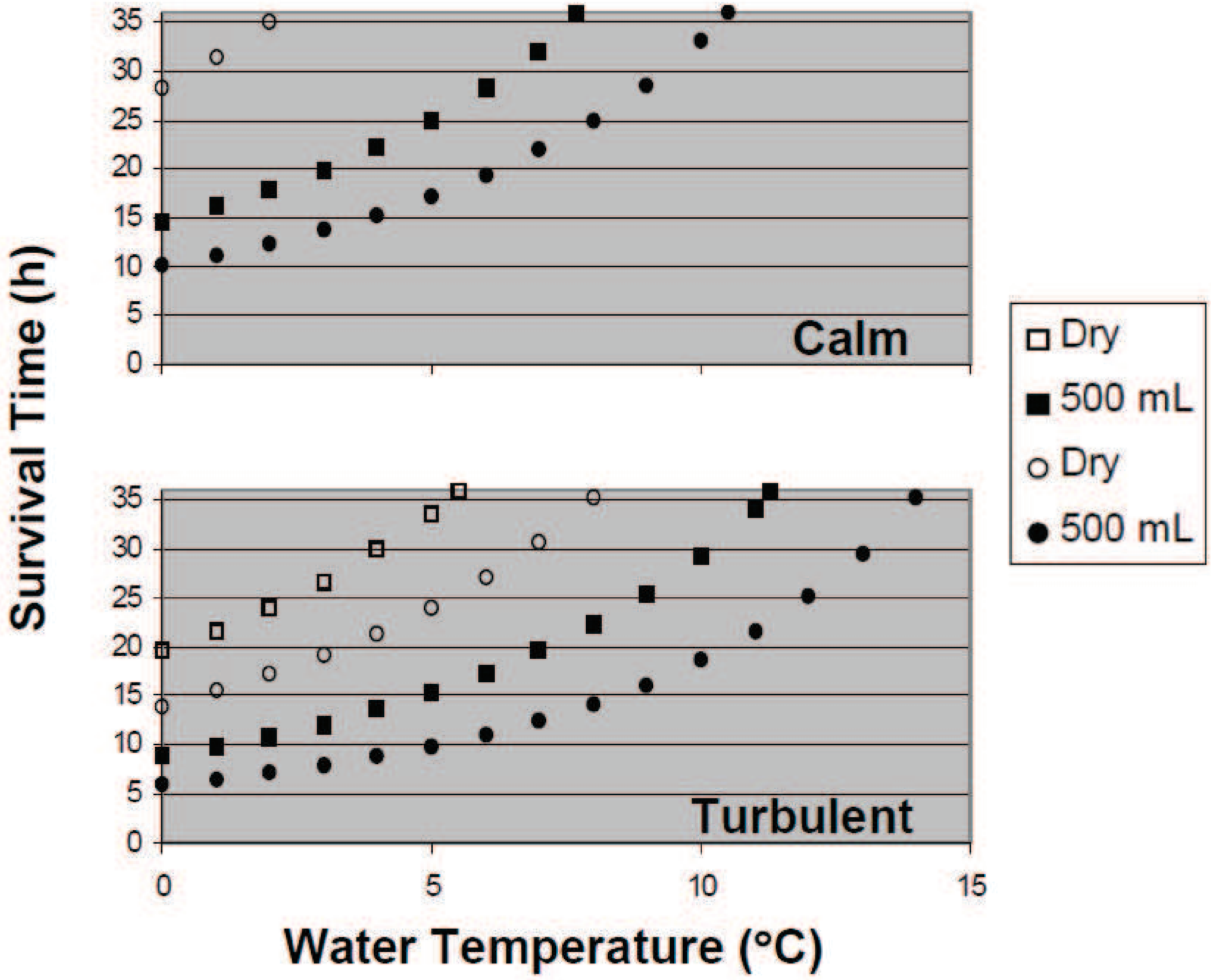

Figure 2. Comparison of predicted survival times for the leanest (○●; 1.79 m, 70 kg, 14.6% body fat) and largest (□■; 1.89 m, 99 kg, 22.8% body fat) subjects immersed in calm and turbulent water under dry and wetted survival suit conditions.

Summary

Although the predicted changes in body temperatures greatly exceed the measured values (Table 1), the subjects cannot be considered 'hypothermic' at the end of 3 h of immersion in 8.5°C water. Hypothermia begins at a deep body temperature of below 35°C (Auerbach 2001), which was not exceeded by either measurement or prediction. Hence, the broader interpretation is that the CESM prediction concurs with the qualitative thermal status of the subjects.

In addition to the explanations offered in the Phase 1 report (Tikuisis 2010) for the overprediction of changes in body temperatures, there is also the possibility in this study that the effect of wetness assumed for the prediction was exaggerated. That is, the 500 mL of water applied to the subjects was assumed to have been evenly spread, which would represent the most severe situation. This is because insulation is degraded disproportionally higher with the initial increment of wetness and less so with further wetness. Hence, if the 500 mL of water was unevenly distributed, then regions with excess wetness would not have had the proportional impact as other regions with less or no wetness, and the resultant cold stress on the subjects would have been less than assumed.

The marked decrease in survival time due to internal wetness of the survival suit, even by a modest amount, was noted in the Phase 1 report (Tikuisis 2010) and is again emphasized in this report. The addition of 500 mL of water to the subjects' clothing diminished predicted survival times by 38 and 44% compared to a dry condition under calm and turbulent water, respectively. However, even when wet, the insulative value of the survival suit is significant when considering how much longer an individual can survive when compared to the nude condition. With 500 mL of water, the suit still extends survivability by about 500 - 800% under calm conditions and between 400 – 600% under turbulent conditions compared to nude (see Figure 1).

Interestingly, turbulence amplifies the degradation of insulation beyond the addition of wetness. This was further demonstrated when comparing the survival times between the leanest and largest subjects of the study. Under a dry condition, the leanest subject would require 13 and 17% more insulation under calm and turbulent water, respectively, to survive as long as the largest subject, and these values increased to 21 and 30% with the addition of 500 mL water to the clothing. Consequently, consideration should be given to the addition of insulation to lean people to provide a similar survival opportunity compared to large people, and that this increase should accommodate the possibility of internal suit wetness, which elevates the required additional amount of insulation.

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